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MAGMATIC CHROMITE DEPOSITS IN SOUTHERN AFRICA.*

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REGIONS STUDIED.

THE occurrences discussed in this paper lie in the Bushveld igneous complex of the Transvaal and in the "great dike" of

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Southern Rhodesia. The deposits of both of these regions are of less commercial importance than those of Selukwe, the World's leading producing district, in Southern Rhodesia, but in the past few years they have received much attention, and the production of the Bushveld has become an important factor in the World's chromite trade, this district, as well as the "great dike," having vast reserves.

METHOD OF STUDY, SUMMARY, AND ACKNOWLEDGMENTS.

The following notes are the result of a microscopic study of the ores and associated rocks undertaken in the hope of establishing definitely the time relations between the formation of chromite and of the associated minerals. Many statements about the relations of chromite and associated silicates are largely distorted by preconceptions of the author as to the physical and chemical processes that controlled deposition. The interpretation of mineral relations has been made to fit the theory instead of modifying the theory according to new evidence.

The present study is concerned principally with rocks of the magmatic stage in the narrowest sense (pyrogenic), which vary from olivine-rich to plagioclase-rich. The time relations of the various minerals here receive particular attention and, after summarizing these relations, various modes of magmatic concentration are considered and compared with the observed facts.

Evidence is presented that chromite in such magmatic deposits crystallizes with the latest silicate minerals rather than with the earliest. Differentiation may concentrate chromium in a residual magma. Although crystal sorting offers a satisfactory explanation of the larger field relations, serious difficulties are encountered in explaining the detailed relations of the minerals by this process without some modification.

The field work on which the present study is based was carried out during and after the XVth International Geological Congress. Every opportunity was taken of visiting chromite occurrences, and some special trips were made. During the regular Bushveld trip of the Congress, special attention was given to minor occur-

rences of chromite, in addition to the commercially important deposits. It is realized clearly that the field work was of a cursory nature and that the number of thin sections studied is small. Nevertheless, it is felt that the main conclusions are supported by very consistent evidence. The significance of the material studied is enhanced by the fact that most of it was collected in the field with the indefatigable guides of the XVth International Congress, Dr. A. L. Hall, Dr. Louis T. Nel, Professor S. J. Shand on the Bushveld trip, and the late Dr. P. A. Wagner on the Rustenburg trip, or was collected by the staffs of various mines and laid out for the members of the Congress. It this way thoroughly representative material was secured. I wish to express my indebtedness to the gentlemen above mentioned, and to the staffs of the Onverwacht, Mooihoek, and Kroondal-Klipfontein (Rustenburg) platinum mines; and to Mr. Geoffrey Musgrave, Consulting Engineer of the Rhodesia Chrome Mines, for guidance at Selukwe and Lala Panzi, and for the benefit of his wide experience with chromite mines in many parts of the World. In particular, I wish especially to record my obligation to Dr. Hall, who gave so freely to the members of the Bushveld trip the benefit of his long and arduous study of the Bushveld region. His selection of the places to be visited made it possible to do in some weeks what otherwise would have taken as many months, if it could have been done at all. Dr. Hall has also supplied information not previously published which the writer has used in Fig. 1. This courtesy is gratefully acknowledged. I am also indebted to an unusual degree to my colleagues, Professors C. H. Smyth, Jr. and A. F. Buddington, and to Dr. C. S. Ross, who read the manuscript critically.

SETTING OF THE CHROMITE DEPOSITS.

Bushveld.

General Geology.—The Bushveld igneous complex[1] is one of the most interesting and varied groups of igneous rocks in the

[1] Hall, A. L.: The Bushveld Igneous Complex. XVth Intern. Geol. Congress Guidebook C 19, 83 pp., 1929. Daly, R. A.: Bushveld Igneous complex of the Transvaal. Geol. Soc. Amer. Bull., vol. 39, pp. 703–768, 1928. Wagner, P. A.: Platinum deposits and mines of South Africa. London, 1929.

world. It occupies a basin-like structure 300 miles across, and is both underlain and overlain by concordant sedimentary rocks which dip more steeply in the floor than in the roof. The upper portion of the complex is granite, and norite predominates in the very diverse lower part. There has been much discussion as to the unity of the upper granite and lower norites, Daly holding that they came into being by differentiation in place, and Hall holding that the granite was intruded later than the norite. The rocks examined in the course of the present study are all from the lower part of the norite portion. Banding parallel to the floor is pronounced, individual pseudo-strata[2] having extraordinary continuity. The lower part of the complex is heterogeneous, and in the "critical zone" many extreme rock types are found. The general relations of the lower part of the complex are shown in Fig. 1, which is based on the data given by A. L. Hall[3] and on a sketch kindly prepared by Dr. Hall for the writer. This sketch shows in a general way the position of the concentrations designated at the left of the column. Hall records the maximum thickness of the whole igneous section here shown as 18,000 feet. The thickness of the various zones are taken in proportion to their maximum outcrop widths as given by Hall in the publication cited.

Any lengthy discussion of the larger phases of the petrology of the complex is out of place here, but several pertinent features may be pointed out.[3a] Repetitions of extreme rock types are com-

[2] The term pseudo-strata has been used by a number of writers for the persistent bands of distinctive igneous rocks parallel to each other and to the floor of the complex.

[3] Handbuch der Regionalen Geologie, Band VII. 7a, The Union of South Africa, pp. 99–103.

[3a] Hall sums up the rock types of the noritic lower portion of the Bushveld complex as follows:

"*Basal or Chill Zone.* Fine-grained noritic rocks. *Transition Zone.* Bronzite-norite, with occasional thin bands of pyroxenite. A little chrome iron. *Critical Zone.* Bronzitite, diallage-norite, etc., serpentine, dunite, chromite, anorthosite. *Main Zone.* Much uniformity over a great thickness. Feeble differentiation. Magnetite bands near top, in contact with anorthosite, much bronzite-norite below. *Upper Zone.* More leucocratic lighter rocks; less basic plagioclase. Bronzite-norite with some diallage-norite." (A composite description taken from Hall's table in XV Int. Geol. Congress Guide Book C-19, p. 23, 1929.)

mon, this being notably the case with the chrome ore horizons each of which is, in turn, multiple. Also, in connection with the question of origin of chromite, it should be noted that banded olivine-rich rocks are almost completely absent from the complex, the best known representatives of this type of rock being the shells

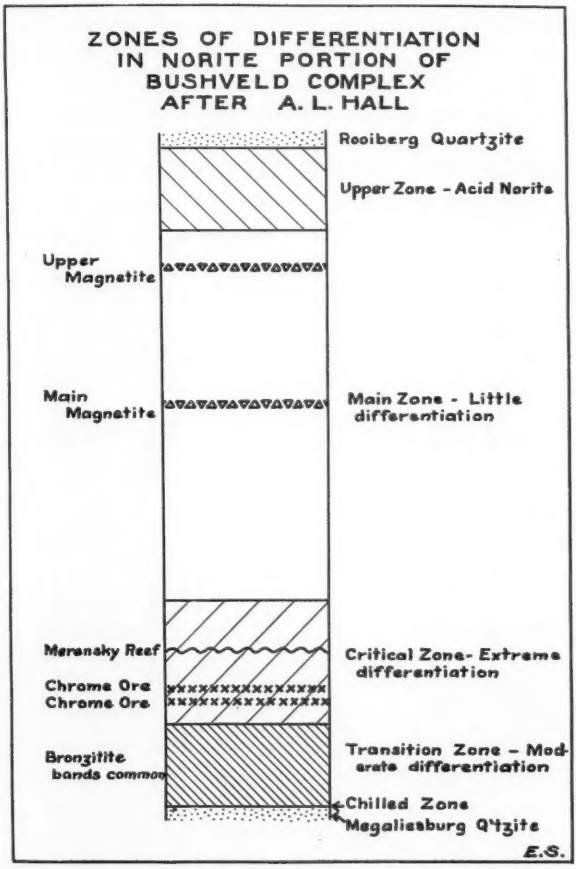

FIG. 1. Zones of differentiation in norite portion of Bushveld Complex. After A. L. Hall.

of the peculiar platinum-bearing pipes, and the pipes are of minute volume as compared to the whole complex.

Chromite Occurrences.—Chromite has formed in many ways within the Bushveld complex. The following occurrences receive attention in this paper: (*a*) disseminated chromite in the dunite of the platinum-bearing pipes; (*b*) the chromitites (chromite-bronzite rocks), which form persistent pseudo-strata and are the workable ores of the region; (*c*) chromite associated with plagioclase, both of which are accessory minerals of bronzitites; (*d*) chromite occurring as clouds within the sulphide-rich platinum-bearing reefs; (*e*) the Dwars River sills, which are intrusive rocks composed of chromite with either plagioclase or bronzite or both; and (*f*) the thin chromite band consistently associated with the platinum-bearing pseudo-stratum, the main source of South African platinum.

"Great Dike."

The "great dike" extends for 330 miles in a northerly direction across Southern Rhodesia.[4] It transects broad regional structures that lie athwart its course. In spite of these dike-like characteristics it shows pronounced, flat-lying bands, very similar to the "norite" portion of the Bushveld complex. The internal structure consists of a series of basins and saddles. The general rock types include various combinations of olivine, enstatite, augite, and labradorite. A common succession described is, in order of superposition:

Rock	*Constituent Minerals*
Feldspar-rich norite	Bronzite Augite Labradorite
Websterite	Bronzite Augite
Bronzitite (serpentinized)	Bronzite
Harzburgite	Olivine Bronzite

The upper part of the websterite contains a platinum-bearing reef almost identical with the "pyroxene-rich diallage norite" of

[4] Provisional Geologic Map of Southern Rhodesia. So. Rhodesia Geol. Survey, 1928. Lightfoot, B.: Platinum in Southern Rhodesia. So. Rhodesia Geol. Survey, Short Rept. 19, 1926. Lightfoot, B.: Traverses along the great dyke of So. Rhodesia. So. Rhodesia Geol. Survey, Short Rept. 21, 1927. Keep, F. E.: Interim report on the geology of the chromite deposits of the Umvukwe Range, Lomagund district. So. Rhodesia Geol. Survey, Short Rept. 23, 1928.

FIG. 2A. Time relations of minerals.

FIG. 2B. Summary of time relations of minerals.

the Bushveld. The main chromite seam at Lala Panzi, where seen by the writer, lies between olivine bronzitite below and strongly serpentinized bronzite dunite above.

DESCRIPTION OF PETROGRAPHIC TYPES.

1. *Pyroxene-free dunite.* Localities: Onverwacht pipe; Mooihoek pipe; Lala Panzi, "great dike."

Dunite Pipes.—These pipes or "parsnip-shaped" masses are perpendicular to the pseudo-strata. They are known only within the "critical zone" of the "norite" portion of the batholith.[5] This would seem to imply that although they are clearly transequent, the magma from which they were formed has migrated but a short distance, or else that the magma from which the overlying part of the batholith was formed was added to the chamber at a later time.

The pipes consist of an inner platinum-bearing core of hortonolite dunite, or (at Driekop) iron-rich olivine dunite, surrounded by a shell of ordinary dunite and in places an outer shell of pegmatitic diallagite, feldspathic pyroxenite, or coarse olivine gabbro. Wagner held that the pipes have formed by replacement, and indeed the shells have many characteristics of reaction rims.

Chromite is abundant in many specimens from the dunite shells studied in this investigation, and its relation to olivine indicates that at least most of it is later. The irregular presence of bronzite in the dunites brings some of the rock into the class of harzburgite, and incidentally has much effect on the distribution of the chromite.

It may be remarked that dunite shells of the pipes contain much rock which in thin section is indistinguishable from bronzite-dunite of the "great dike" of Southern Rhodesia. This is so much the case that in discussing paragenetic relations the two very different field occurrences may be considered together. The mineral similarity offers considerable material for thought in

[5] Wagner, P. A.: *op. cit.*, p. 52.

considering the origin of the pipes, a subject outside the scope of the present investigation.

The rock of the dunite shell of these pipes varies considerably in content of bronzite. The relation of the chromite to olivine depends on the presence or absence of bronzite, so that different relations may be seen even in a single thin section. For this reason these two phases of the dunite of the pipes are considered separately. Under the present heading (Type 1) only the pyroxene-free dunite is described, the bronzite-dunite and harzburgite of the pipes and the " great dike " coming under Type 2.

Petrographic description.—Most of the chromite of the pyroxene-free dunite is interstitial to the olivine, although a small part of the chromite occurs as small subhedral grains within the olivine. Both kinds of chromite are shown in Fig. 3. In addition to these forms, more or less euhedral grains are concentrated between the olivine grains. As the concentration increases, this sort of structure approaches the type shown in Fig. 3, where solid chromite fills the interstices of rounded olivine grains. In places the chromite grains included in the olivine themselves include small specks of olivine. The orientation of the olivine within the chromite is different from the orientation of the olivine surrounding the chromite, showing that the chromite within the olivine has not been formed by replacement. I consider that this chromite formed during the crystallization of the olivine, whereas the interstitial concentrations of separate grains and the solid interstitial chromite moulded against olivine grains is mostly later than the olivine. This time relation is indicated in Fig. 2*A*, Type 1.

2. *Pyroxene-bearing dunite and harzburgite.* Localities: Onverwacht pipe; Mooihoek pipe; Lala Panzi, " great dike."

The presence of a little bronzite greatly alters the relations of chromite. Minor amounts of bronzite are distributed unevenly through the olivine dunite of the pipes; and bronzite, though of uneven distribution, in the olivine-rich rock of the " great dike " at Lala Panzi, on the whole brings the rock within the range of harzburgite.

Where bronzite has formed, the crystals have grown largely at the expense of olivine, such replacement having gone far in some of the rock at Lala Panzi (Figs. 4, 5, 6). In such areas the

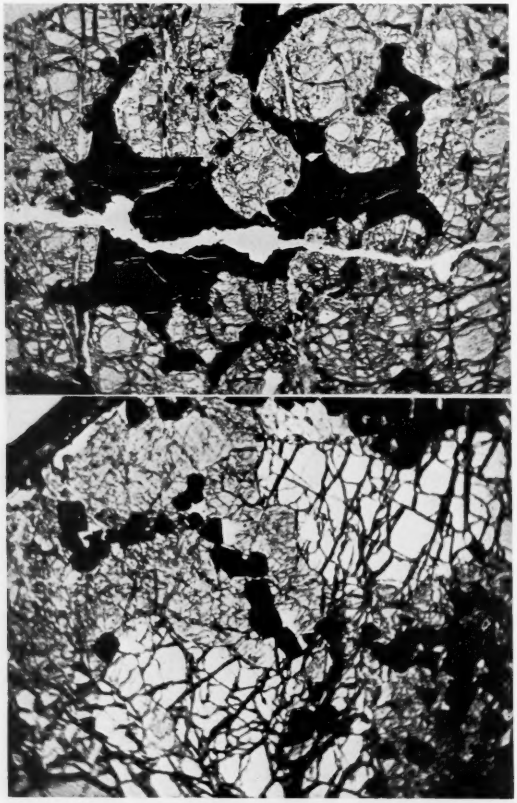

FIG. 3 (Top). Chromite included in, and moulded on, olivine. Lala Panzi, "great dike." × 18.

FIG. 4 (Bottom). Chromite in bronzite, interstitial to olivine. Band at upper left is edge of section. From olivine dunite shell of pipe, Mooihoek platinum mine, Bushveld. × 19.

replacement of olivine by bronzite is clearly evident, the olivine grains being smaller than in that part of the section where no bronzite has formed. Fig. 5 shows the replacement carried to

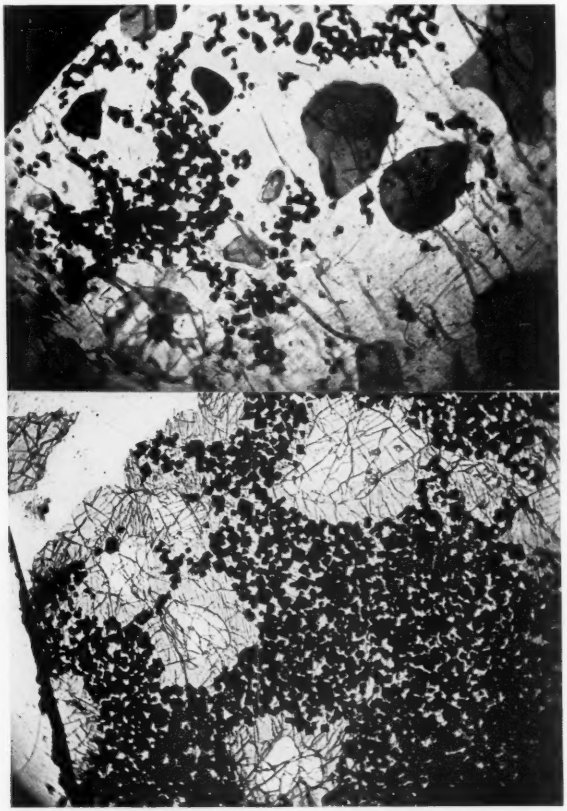

FIG. 5 (Top). Chromite included in single crystal of bronzite which also includes corroded remnants of olivine. Band at upper left is open field. Lala Panzi, "great dike." Crossed nicols. × 20.

FIG. 6 (Bottom). Corroded olivine in bronzite. The chromite-free areas in the bronzite are thought to represent olivine replaced by resorption. Edge of section in lower left. Lala Panzi, "great dike." × 14.

a stage where only small corroded remnants of olivine are left. The hand specimen illustrated by Fig. 5 consists in part of nearly pure olivine on which bronzite (with chromite) has encroached, forming large poikilitic bronzite crystals an inch or more in size containing easily recognizable olivine inclusions. This replacement represents reaction of olivine with magma, and one is led to believe that such reaction may in part account for the great rarity of olivine-bearing rocks in the Bushveld, although bronzitites are common.

In the early stages of the growth of bronzite (Fig. 4), lines of euhedral chromite crystals mark the boundaries of olivine grains, and, as mentioned under Type 1, such interstitial chromite crystals may occur where bronzite is absent. Such chromite clouds as in Fig. 5 commonly contain in the central portion crystals larger than in the surrounding cloud, and of the same size and distribution as the lines of chromite crystals between olivine grains, as shown in Fig. 3. These larger crystals of Fig. 5 may well be earlier than the bronzite, but it is thought that the small crystals forming the cloud are contemporaneous with the bronzite.

Fig. 6 shows rock richer in chromite, the clear areas of bronzite around the olivines perhaps being explained by reaction by diffusion.

The time relations of the minerals olivine, bronzite, and chromite in these rocks are shown in Fig. 2*A*, Type 2.

3. *Chromitite.* Localities: Grootboom chromite mine, Mooihoek chromite mine, Lala Panzi chromite mine.

Wagner proposed the term chromitite for the chromite-bronzite rocks of the Bushveld.[6] These rocks form the main chrome ores of the Transvaal and are the greatest concentrations of chromium known in the world.

The bands are up to five feet or so in thickness and of great continuity. The chromitite seems to bear complementary relation to anorthositic rock, the two being found in close association.

In the typical rock (Fig. 9) large rounded bronzite crystals

[6] Wagner, P. A.: The Chromite of the Bushveld Igneous Complex. South African Jour. Sci., 1923, pp. 223–235.

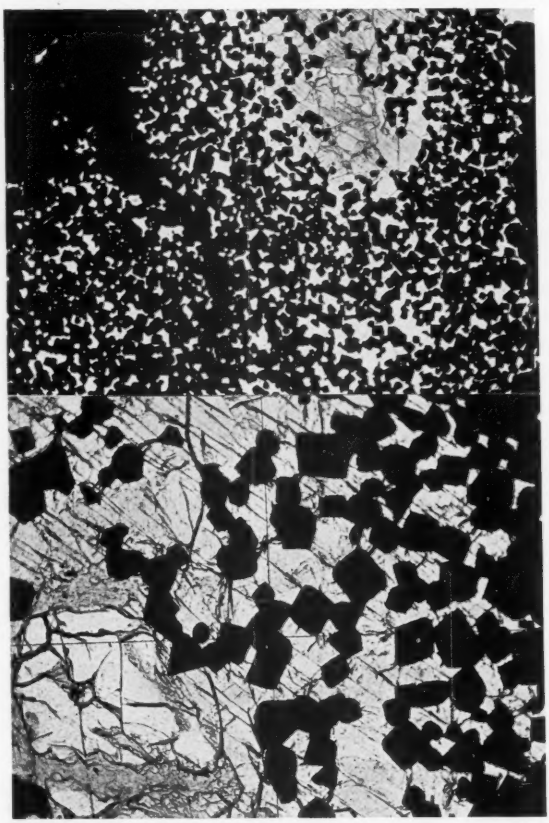

FIG. 7 (Top). Olivine chromitite. Core of serpentinized olivine in bronzite. Bronzite includes, poikilitically, chromite with chain structure. Only two bronzite crystals are shown, separated by band of solid chromite. The interstitial chromite is much coarser than the included chain structure chromite. Lala Panzi, "great dike." × 17.

FIG. 8 (Bottom). Chain structure of chromite in olivine chromitite. Same field as in Fig. 7. Lala Panzi, "great dike." × 52.

poikilitically include a host of minute idiomorphic chromite crystals. Solid granular chromite may also fill spaces between the bronzite crystals. The bronzite may have a clear core or may contain chromite rather uniformly throughout. The chromite generally is somewhat coarser grained and more abundant towards the margin of the bronzite.

The chromitite of the "great dike," which I saw at Lala Panzi through the kindness of, and in company with, Mr. Geoffrey Musgrave, Consulting Engineer of the Rhodesia Chrome Mines, contains some olivine, and the interstitial chromite is much coarser with respect to the chromite in the bronzite than is the case in the Bushveld (Figs. 7 and 8). The olivine occurs as cores within the bronzite and is free from chromite except for a few crystals at the margin.

This occurrence of olivine in chromitite of the "great dike" forms an interesting tie between the olivine-rich rocks of the "great dike" and the abundant olivine-free ultrabasic rocks of the Bushveld.

In these rocks chromite and bronzite formed contemporaneously, as indicated by the clear bronzite cores occasionally seen, and by the even gradation in distribution of the chromite from the center outwards that is found in some of the rocks, a feature which Wagner emphasized.

A marked difference in size of grains is apparent between the chromite within the bronzite and the chromite interstitial to the bronzite. The interstitial chromite is much coarser, as is indicated by Fig. 7.

The time relations of the minerals of the chromitites are indicated in Fig. 2, Types 3*A* and 3*B*. Type 3*A* is the olivine-bearing chromitite of Lala Panzi, and Type 3*B* the olivine-free chromitite of the Bushveld.

Chain Structure.

One feature encountered in the chromitites deserves special mention, although its origin is not entirely clear, namely, the occurrence of series of connected chromite crystals somewhat

resembling a chain. The crystals are octahedra and are connected at the apices. The chains may branch by crystals attached to two or more apices of an octahedron, but it is noticeable that the chains do not maintain any regular geometric pattern like common skeletal growths, rather are the chains curved. The individual crystals of the chains are always minute, being commonly about 0.1 mm. in size, as compared to chromite crystals interstitial to the bronzite, which are many times that size.

This chain structure is met with in a number of the chromite occurrences of somewhat dissimilar nature and mineral composition. Intergrowths of chromite and bronzite are seen in Types 2, 3, and 4 (Figs. 5–9), and exactly similar intergrowths of chromite and plagioclase are found in Types 5 and 6 (Figs. 11–14 and 17–19). The plagioclase in all rocks tested is uniformly close to basic labradorite, An_{67}.

This peculiar structure would seem to indicate similar physical conditions of crystallization of the rocks in which it is found, but although high viscosity of the magma suggests itself, this is not a very satisfactory explanation, and the question must remain open. However, the conclusion seems clear that the chromite grew in place simultaneously with the silicate.

4. *Chromite-bronzite rock.* Localities: Mooihoek chromite mine, Jagdlust farm, near Olifants River.

Wagner included in his term chromitite a type of rock which is here described separately, namely, a rock consisting of crystals of clear bronzite with interstitial chromite and, commonly, plagioclase. To the present writer it would seem better to restrict Wagner's useful term to the main and unique type of rock in which chromite is scattered poikilitically through bronzite as minute crystals and also, to greater or less degree, is found in larger crystals interstitial to the bronzite. In the chromite-bronzite rock now to be described the chromite is clearly later than the bronzite and has in part replaced it. Plagioclase also occurs with the chromite, as does a little biotite. These features make this type of rock an important connection between the chromitites, in the restricted sense (Type 3) and Type 5.

In the rock now under discussion the amount of chromite differs greatly according to the extent that replacement of bronzite by chromite has taken place. This varies from very little, as in Fig.

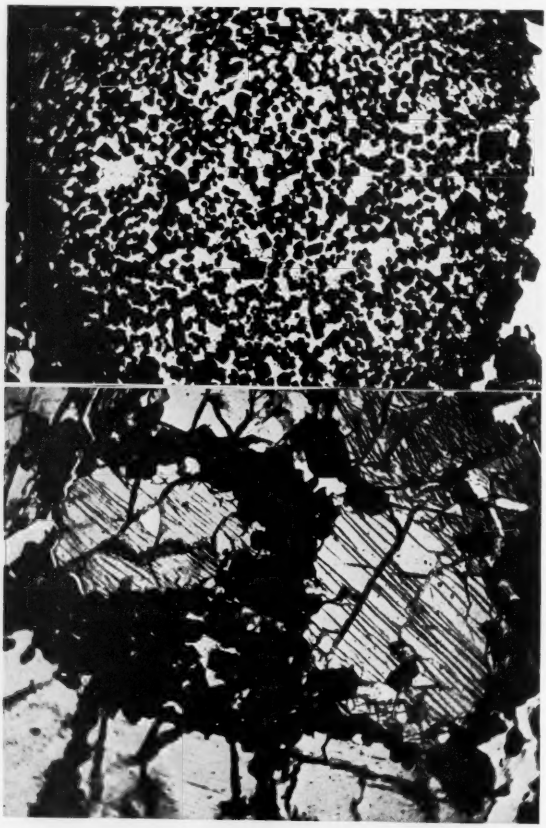

FIG. 9 (Top). Characteristic chromitite. Single crystal of bronzite including chromite in chain structure and surrounded by coarsely crystalline interstitial chromite. Mooihoek chromite mine, Bushveld. × 16.

FIG. 10 (Bottom). Chromite with plagioclase interstitial to bronzite from chromite-bronzite-rich band in anorthosite. Jagdlust farm, Olifants River, near Malips Drift, Bushveld. × 20.

10, to a rock composed of rounded grains of bronzite contained in predominating chromite.

The paragenesis of this type is indicated by Fig 2*A*, Type 4.

5. *Platinum-bearing reef.* Locality: Forest Hill platinum mine.

This type of rock is illustrated by but one South African locality studied in detail by the author, though a number of apparently similar occurrences were seen in the field. This locality is the Forest Hill platinum mine, and the relations are there so clearly shown and are of such significance as to be important. The rock is composed of clino-bronzite and labradorite (An_{67}) and contains considerable sulphide. Through this rock are stringers formed of clouds of chromite crystals, the distribution of the crystals varying from fairly compact to scattered. These chromite clouds are different in occurrence from the chromite of the " chrome band," which is a constant associate of the Merensky reef. In thin section the chromite is seen to be closely associated with the plagioclase, although plagioclase may occur without chromite. Chromite-rich plagioclase belts run the width of the section, and in these belts (Fig. 11) the chromite, although mostly in the plagioclase, also occurs at the edges of, and well within, the bronzite. These chromite crystals within the bronzite are almost all rimmed with plagioclase.

One other feature deserves mention as bearing on the type of rock to be discussed next. In the same section as illustrated in Fig. 11 is a large feldspar area which contains chromite crystals of two different sizes (Figs. 12, 13). The smaller crystals form in a striking fashion the chain structure described above. The relations of chromite and plagioclase to bronzite in this type of rock (Type 5) I take to indicate replacement of bronzite by chromite and plagioclase simultaneously. A corollary of this conclusion is that both the chromite and plagioclase have crystallized in place.

This late crystallization from an interstitial liquid is of interest in connection with the next type to be discussed, for if the interstitial liquid be squeezed out, a rock composed essentially of

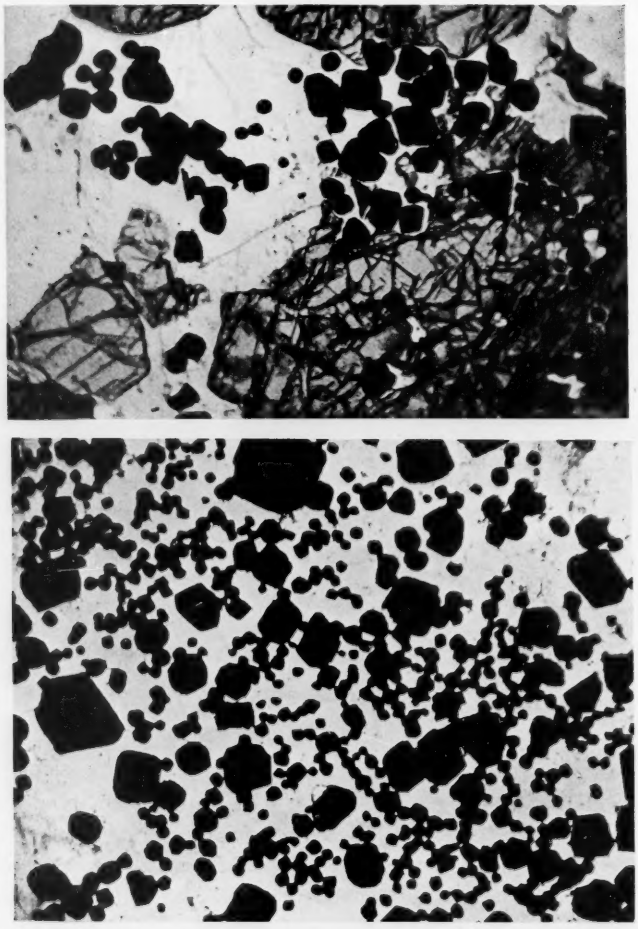

FIG. 11 (Top). Chromite and labradorite replacing bronzite. From sulphide-bearing Merensky Reef. Forest Hill platinum mine, Bushveld. × 20.

FIG. 12 (Bottom). Chromite showing chain structure, in labradorite. Same thin section as Fig. 11. Forest Hill platinum mine, Bushveld. × 20.

plagioclase and chromite might form, and this I believe may account for the peculiar rocks of Type 6.

Fig. 2*A*, Type 5 shows the interpretation of the time relations of the minerals above described.

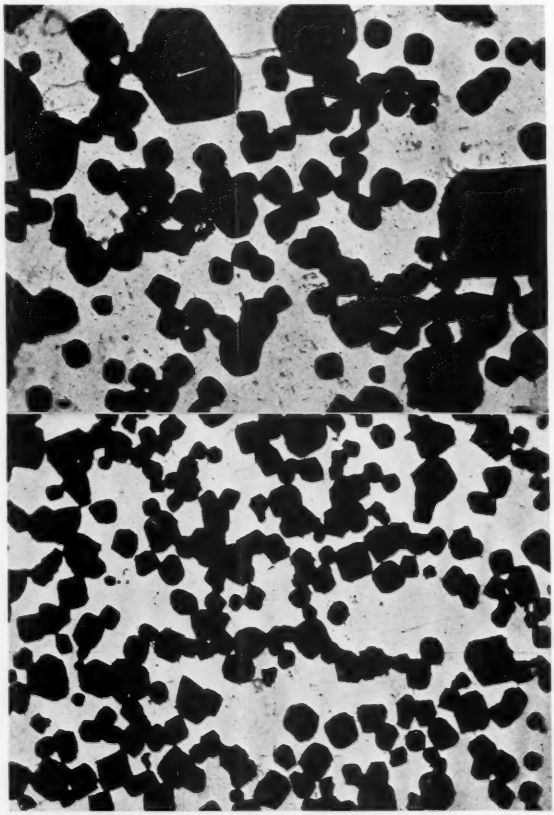

FIG. 13 (Top). Chromite showing chain structure, in labradorite. Same thin section as Figs. 11 and 12. Forest Hill platinum mine, Bushveld. × 77.

FIG. 14 (Bottom). Chromite showing chain structure, in labradorite. From same rock as section of Fig. 19. Dwars River, Bushveld. × 54.

6. *Chromite-plagioclase-bronzite rock.* Locality: Dwars River.

This rock is remarkable in that it is clearly intrusive and contains chromite as a major constituent together with plagioclase and bronzite (Figs. 14 and 17–19). It forms a most remarkable series of sills in anorthositic norite at the crossing of the Dwars River on Dwars River Farm. Many of the sills [7] are but a fraction of an inch thick, and they range from that thickness to several feet (Figs. 15 and 16). At first glance they appear to be strictly parallel, but on being followed are seen to split and reunite. The largest sills show sharp inclusions of anorthosite torn from the walls, as shown in Fig. 16, for which I am indebted to Professor F. F. Grout. In addition to the clear cut sills, minute isolated stringers some millimeters long are found in the anorthositic norite between the sills.

The rock is composed of a ground mass of poikilitic plagioclase or bronzite, or both, through which small chromite crystals are scattered. The chromite is for the most part in a uniformly distributed chain structure, though a small part of it occurs as decidedly bigger crystals in between the larger silicate crystals (Fig. 17). With this interstitial chromite considerable biotite is found.

The boundaries of the sills and the anorthositic norite walls present features difficult to explain. The plagioclase of the sills is of the same composition as that of the wall rock (An_{07}), but it occurs in larger crystals nearly free from the albite twinning universal in the anorthosite. There is, however, a zone in the marginal part of the sills where the plagioclase containing chromite is continuous with clear plagioclase crystals of the wall rock, as shown in Figs. 18 and 19. The line between the chromite-bearing rock and the chromite-free rock is commonly sharp and runs across plagioclase crystals, but in places sends projecting clouds of chromite crystals into the wall rock.

It seems to me that the explanation of these sills is that the crystallized anorthosite was cracked and into these cracks was in-

[7] These are referred to as sills because of their concordance with the general pseudo-stratification of the surrounding rocks.

troduced a chromite-bearing residual magma from which crystallized a plagioclase of the same composition as that of the anorthosite, and, somewhat later, bronzite. The plagioclase formed on the wall in parallel growths as extensions of the wall rock plagioclase, and away from the wall with its own distinctive habit.

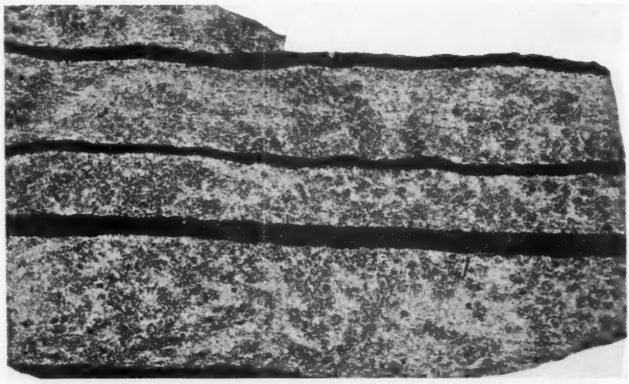

FIG. 15 (Top). Sills of chromite-plagioclase-bronzite rock in anorthositic norite. Dwars River, Bushveld. × 0.3.

FIG. 16. Inclusion of anorthositic norite in sill of chromite-plagioclase-bronzite rock. Dwars River, Bushveld. Photograph by F. F. Grout.

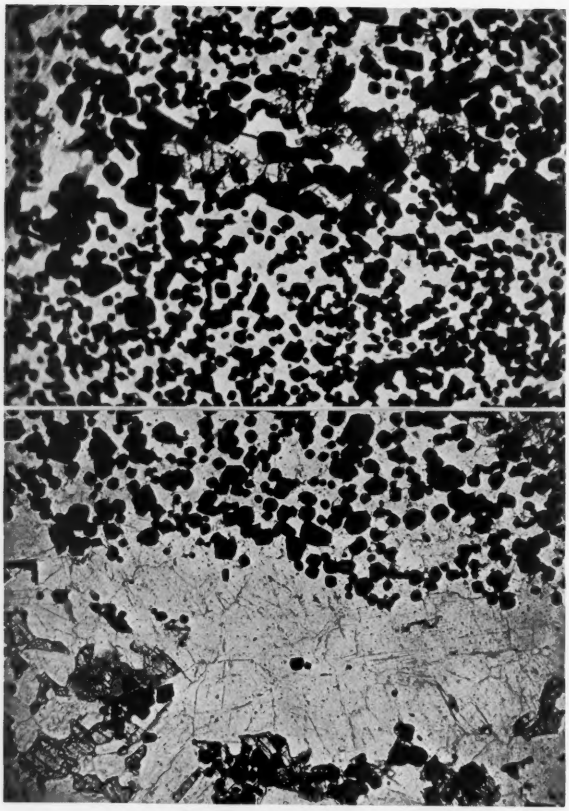

FIG. 17 (Top). Chromite in coarsely crystalline plagioclase. Shows band of coarser-grained chromite with bronzite and biotite at junction of two plagioclase crystals. Sill of chromite-plagioclase-bronzite rock. Dwars River, Bushveld. ×20.

FIG. 18 (Bottom). Boundary of chromite-plagioclase-bronzite sill with anorthositic norite. Stringers of chromite with bronzite and biotite developed in wall rock. Dwars River, Bushveld. ×17.

Chromite occurs also as stringers in the anorthositic norite and in these stringers is commonly associated with bronzite, and in some with a monoclinic pyroxene. Biotite also is common. Such stringers, but without monoclinic pyroxene, are shown in Fig. 18. The bronzite shows little or no replacement of the plagioclase, but the monoclinic pyroxene has brought about considerable replacement. A few chromite crystals, although usually near ferromagnesian silicates, are isolated and probably formed by replacement, although their sharp euhedral character makes this conclusion difficult to prove. These stringers in the anorthositic norite are all parallel to the main sills and probably are closely allied to the sills representing injection into incipient cracks rather than into the stronger fractures which produced sills.

The mineralogical succession of the Dwars River sills is represented by Type 6 of Fig 2*A*.

Chromite Band with Merensky Reef.

A persistent feature of the platinum-bearing reefs of the Bushveld are bands of chromite. Wagner states that such bands of chromite occur at various horizons, and the observations of the present writer would lead him to suggest that the chromite of the platinum reef is not all of the same origin. One variety of chromite from the platinum reef has already been described (Type 5). The chromite of the Klipfontein-Kroondal mine of the Rustenburg district is, however, of such a peculiar nature as to require some comment. The author realizes fully the importance of field evidence in discussing any feature of the platinum reefs, and for this reason has not included the chromite now to be described in the grouping of the other types; but the laboratory study of a number of specimens from this one mine discloses features which warrant description, even if they cannot be adequately interpreted.

At the Klipfontein-Kroondal mine the footwall rock is anorthositic norite. At the very top of the anorthositic norite is a narrow band of pure anorthosite with no bronzite. It has an undulatory upper surface and varies abruptly in thickness from a

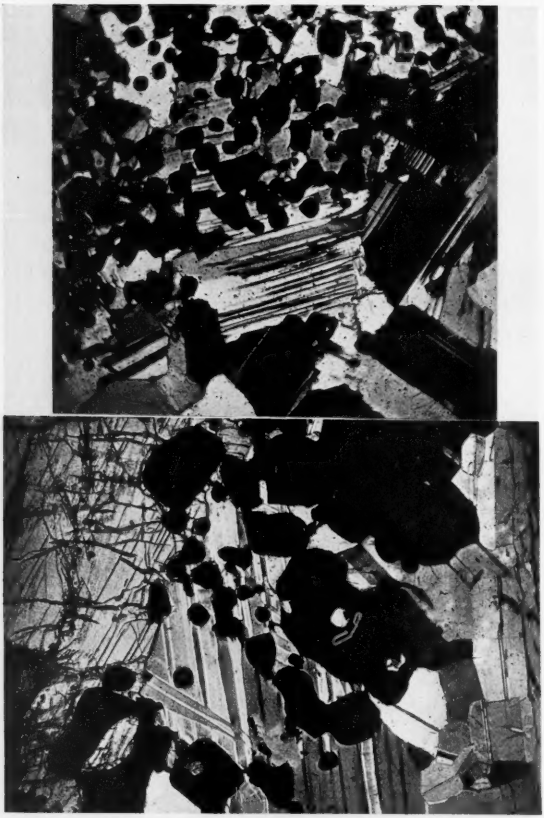

FIG. 19 (Top). Central part of field illustrated in Fig. 18 showing boundary of "sill" extending through a crystal of labradorite. Dwars River, Bushveld. Crossed nicols, × 52.

FIG. 20 (Bottom). Section showing entire width of narrow "chrome band," at base of sulphidic platinum-bearing reef. Anorthositic band of footwall at right; platinum-bearing reef at left. Note independence of chromite to boundaries of silicate grains and note that plagioclase intergrown with chromite is continuous with that of footwall rock. Crossed nicols, × 16.

fraction of an inch to a little over an inch. In places it contains specks of sulphide. Above this band is the chromite band commonly less than an inch thick, rarely as much as two inches. The bottom of the band is sharply defined, but the top is irregular and in places sends cloud-like protrusions into overlying feldspathic pyroxenite.

Studied with the microscope, the chromite band is seen to consist of chromite embedded in labradorite (An_{66}) and bronzite. Where the band is thin the chromite is entirely in the form of peculiar embayed masses (Fig. 20). Fig. 21 shows an extreme, though by no means unusual, degree of irregularity. Where the band is thicker, a gradation may be seen from the embayed form of chromite at the bottom to a mixture of embayed and chain structure chromite at the top. The crystals of the chain structure are much smaller than the embayed chromite masses. A section showing the two forms of chromite is illustrated in Fig. 22. In the plates illustrating the chromite band several examples may be seen of single crystals of chromite completely surrounding an included area of plagioclase. For the most part, these are to be explained as being sections showing the bottom of an embayment of plagioclase into chromite, although in some instances it would seem possible that plagioclase served as a nucleus for the growth of chromite. Similar inclusions of bronzite in apparently unembayed chromite, in turn contained in bronzite, are seen in the olivine-rich rock at Lala Panzi, an example being shown at the top of Fig. 4. In the illustrations of the chromite band from Rustenburg, it is to be noted that the chromite is included in larger plagioclase crystals without any regard to the boundaries of these crystals. The plagioclase crystals interlock tightly, and apparently at least completed their growth in place. Fig. 20 which illustrates the entire width of the chromite band, shows that the bronzite of the overlying sulphide-bearing reef is moulded on the chromite. It would seem that the best explanation for these irregular chromite crystals is that they are relics of resorption and that they are the result of settling, the surrounding plagioclase and bronzite having grown about them in place.

FIG. 21 (Top). Corroded chromite in labradorite. From same thin section as Fig. 17. Note independence of chromite to boundaries of plagioclase grains. Klipfontein-Kroondal mine, Rustenburg, Bushveld. Crossed nicols, × 16.

FIG. 22 (Bottom). Corroded and chain structure chromite from base of thick portion of "chrome band." Klipfontein-Kroondal platinum mine, Rustenburg, Bushveld. × 18.

The chain structure chromite associated with the embayed chromite is perhaps the result of recrystallization of material previously resorbed from the embayed chromite. The bearing of all this on the origin of the immediately overlying platinum-bearing reef is a matter of much interest though beyond the scope of the present paper.

CHROMITE AND MAGMATIC DIFFERENTIATION.

The types of chromite occurrences which have been described yield considerable information on the course of magmatic differentiation. In all these rocks the chromite crystallized from a magma, considered in a narrower sense as a solution, liquid mainly because of high temperature, and containing but minor amounts of volatiles. The Dwars River type, however, contains a moderate amount of biotite, and differentiation is well along toward the hydrothermal stage in which the solution owes its fluidity rather to volatiles than to high temperature.

The time relations of the minerals in the various types of occurrences are shown for comparison in Fig. 2*A*. The relations of the minerals in any one type are fairly well substantiated, but the time relation of any one mineral common to several types is necessarily somewhat arbitrarily shown. These relations are summarized in Fig. 2*B*. Fig. 2 indicates that in the types there represented the chromite crystallizes with the latest silicate mineral or alone after the silicate minerals.

The chromite deposits of the Bushveld and the "great dike" form a distinct class of deposits whose individuality has not been generally appreciated. In a recent paper [8] the writer advocated a classification of chromite deposits into early magmatic, late magmatic, and hydrothermal varieties. The deposits discussed in this paper form a broad group of closely related origin in that they are all associated with a petrographic series characterized by the formation of extreme rock types of which bronzite-rich and labradorite-rich rocks are conspicuous. The chromite is in small part early magmatic and for the most part late magmatic.

[8] Sampson, Edward: Varieties of chromite deposits. ECON. GEOL., vol. 26, pp. 833–839, 1931.

The fact that chromite deposits in many parts of the world are so frequently associated with olivine-rich rocks or serpentines derived from them has resulted in particular, and probably undue, emphasis being placed on the essential contemporaneity of olivine and chromite. The intensity of serpentinization has in many instances rendered impossible the determination of the relation of chromite to early silicates. In the Bushveld and the "great dike," on the other hand, little serpentinization has taken place on the whole, and the main concentrations of chromite are with minerals other than olivine.

Two generalizations appear to be in order, although from the point of view of the complete control of differentiation by crystal sorting they conflict with each other. First, chromite is concentrated with the most basic members of the petrographic series whose major constituents are assumed to be settled silicate crystals; and second, the texture is such as to indicate that the chromite crystallized in place from a solution which must have been rich in chromite.

For the occurrences described in the present paper, difficult questions are raised as to the physical conditions during crystallization. To what extent are the extreme rock types due to the crystallization in place of a magma of essentially the same composition as the resulting rock? And to what extent does crystal sorting explain relations? Can the settling of an immiscible chromite liquid be called upon? Although on the whole, crystal sorting accounts for many of the larger field relations difficult of explanation otherwise, the detailed mineral relations of the rocks of the present study offer serious difficulties to this view without modification. Chief of the difficulties are the definite mineral successions within the rocks and the association of minerals, the presence of each of which requires concentration. The chromite presents the main problem, for the residual liquid which contains it is itself a concentrate, and not what might be expected from ordinary magma into which the earlier formed crystals fell.

Table I is offered as an analysis of possible causes of concentration of the chromite deposits discussed in the present paper.

TABLE I.

PROCESSES CONCEIVABLY ACCOUNTABLE FOR CHROMITE-RICH ROCKS.

TABLE I.

PROCESSES CONCEIVABLY ACCOUNTABLE FOR CHROMITE-RICH ROCKS.

Process.	Results.	Applicability of Process.
I. SORTING OF CRYSTALS		To account for chromite it is necessary to have an accumulation of both chromite and silicate crystals, but structures such as the chromitite (Type 3) and chromite-plagioclase rock (Type 6) show intergrowth in place of chromite and silicate. Cannot account for presence of chromite intergrowth with other minerals (Types 2, 5) replacing earlier silicates unless there be complete melting and recrystallization.
(*a*) Host magma does not affect sorted crystals.	Interstitial minerals either by contemporaneous shower or from interstitial liquid.	See objections under I. Chromite formed by replacement would have to come from magma surrounding sorted crystals, and this magma would probably have to be even richer in chromite than the present rock.
(*b*) Solution of sorted chromiferous crystals.	Sorted crystals show corrosion. Interstitial minerals from contemporaneous shower or from magma surrounding sorted crystals, but modified by addition from dissolved crystals.	See objections under I and I-*a*. The relic minerals are not chromium-rich and therefore could not have enriched the interstitial magma in chromium.
(*c*) Reaction of sorted chromiferous crystals with magma.	Sorted crystals may or may not show corrosion. Interstitial minerals from contemporaneous shower or from magma surrounding sorted crystals, but modified by interchange with included crystals.	Same as I-*b*.
(*d*) Sorted crystals melted.	To be preserved as a distinct rock the new magma must not mingle extensively with adjacent magma. Rock owes main distinguishing features to elements concentrated by sorted crystals. Elaborate succession of minerals possible.	Would require long time for melting and subsequent cooling to crystallization; during this time the liquid would have to remain distinct. As far as microscopic evidence goes, this is a satisfactory theory. The final answer depends on field relations.

TABLE I.—*Continued*

Process.	Results.	Applicability of Process.
II. Settling of Silicate Crystals and Chromite-rich Liquid		Does not explain inclusion of chain structure chromite in silicate crystals (Types 3, 5, and 6).
(*a*) Chromite liquid arrives and crystallizes before arrival of silicate crystals.	No intergrowth of chromite and settled crystals.	See objection under II. Late stage of all chromite rules this out.
(*b*) Chromite liquid crystallizes after arrival of settled crystals.	Chromite surrounds settled crystals.	See objection under II.
1. Chromite liquid unmodified by host silicate liquid.	Interstitial intergrowth of chromite and silicates unlikely.	See objection under II. Replacement of early crystals simultaneously by silicate and euhedral chromite indicates one, and not two, replacing liquids. (Types 2 and 5.)
2. Chromite liquid modified by host silicate liquid.	Interstitial intergrowth of chromite and silicates possible.	See objection under II.
3. Chromite liquid unites with interstitial silicate liquid.	Interstitial intergrowths of chromite and silicate probable.	Satisfies evidence for one late chromite and silicate-bearing liquid.
III. Separate Chromite-rich Magma	Full succession of minerals.	Field evidence strongly against persistent bands, such as chromitites (Type 3), being formed by separate intrusions, although the migration of a residual magma well explains minor occurrences, commonly with replacement (Types 2 and 5), and the Dwars River sills (Type 6).

The first column gives processes which may be imagined to have taken place; the second column lists some of the effects which would be produced by the supposed process; and in the third column is an analysis of the applicability of the process for the occurrences described.

The results of this analysis show that there are only two processes which are not opposed by contradictory facts of the microscopic study. These processes are the remelting of sorted crystals and, to a limited extent, the separate intrusions of magma. These theories must stand the test of physical-chemical knowledge, and above all of field studies. Information is not as complete as could be wished for either of these tests.

The theory of refusion has much to favor it for the persistent chromite bands (Type 3). This allows crystal settling to bring about the main concentration, and it accounts in a satisfactory manner for the stratified nature of the deposits and postulates crystallization in place, which would explain the detailed relations between the minerals. The main objections to the theory are physical-chemical. The objection of quantity of heat available is not serious, in view of the infinitesimal size of the chromitite deposits as compared to the magma chamber; but the objection as to the melting point of the chromite is serious. However, if the chromite was not brought into the magma chamber as crystals, and if therefore it crystallized at a higher and cooler level, it might have settled into an environment such that conditions might have been reversed and the chromite passed again into solution. The arguments advanced below indicate that chromite stays in solution far below its dry melting temperature. The point of this argument is that the writer would suggest the possibility of the formation of the chromitite by refusion of settled crystals, and would urge that the hypothesis be not thrown out arbitrarily on the basis of our present physical-chemical knowledge. It seems that there are essential facts that we do not know.

The second theory which seems to fit the facts is the simultaneous formation of chromite and silicate from a residual solution. The evidence presented in the body of this paper seems to the

author to substantiate this view. Given a sufficient amount of migration, this process may result in the actual intrusion of a chromite-rich magma. The author believes that a number of the types of occurrences described in this paper show a succession of stages by which chromite is strongly concentrated in a residual magma.

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PRINCETON, NEW JERSEY.

A PITCHBLENDE–SILVER DEPOSIT, GREAT BEAR LAKE, CANADA.[1]

D. F. KIDD.

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INTRODUCTION.

DURING the spring of 1930, pitchblende and native silver were discovered at a point on the east side of Great Bear lake, Northwest Territories, Canada. In the course of field work in 1931 for the Geological Survey of Canada the author had the opportunity of examining some of the discoveries, and this paper deals with the deposit on which the greatest amount of development work has been done. In view of its unusual character for this continent, and its reported richness, this preliminary paper may be of interest.

Great Bear lake lies on the Arctic circle, 150 miles east of the Mackenzie river. The silver and pitchblende discoveries are near Echo bay, at the middle of the east shore of the lake, about 35

[1] Published with the permission of the Director, Geological Survey of Canada, Department of Mines, Ottawa. Presented before Society of Economic Geologists, Tulsa Meeting, Dec. 29, 1931.

miles south of the Arctic circle. The deposit is at LaBine point, the north point of the bay. It is 850 miles by the air route north of the railhead at Waterways, Alberta, which in turn is 300 miles by rail north of Edmonton, Alberta. By the usual route down

FIG. 1. Airplane view of LaBine Point, Great Bear Lake, looking south from an altitude of 5000 feet. The hills in the foreground rise 500–700 feet above the lake. The scarp in the center of the picture marks the outcrop of a basic sill dipping to the left. (Photo courtesy R. C. A. F.)

the Mackenzie system to Fort Norman, up Great Bear river and across the lake it is 1380 miles from Waterways. In an average season the district can be reached by aircraft on floats from about July 1 to September 8, and by aircraft on skis from December 15

to April 10. Boats can travel on Great Bear lake in August and September.

The region is rugged, with considerable relief. Within a few miles of the lake the hills rise 1000 feet or more, and shore cliffs several hundred feet high are not unusual. Rock exposures are excellent (Fig. 1). Scrubby timber is found up to 700 feet above the lake.

GENERAL GEOLOGY.

Preliminary areal mapping indicates two minor and three major rock types. These are:

Basic dikes and sills; large quartz veins.
Flat-lying sandstones and conglomerates.
Granitic and other acid plutonic intrusives.
Folded sediments and volcanics.

All are probably pre-Cambrian in age.

The largest group is the folded sediments and volcanics. These comprise tuffs, conglomerates, sandstones and quartzites, agglomerates, flows, banded fine-grained sediments (in part probably of volcanic origin), cherts, lean iron formation, limestone and dolomite. It is entirely possible that these rocks belong to two or more major series but so far in the present exploration no attempt has been made to subdivide them. Intruding these rocks are granitic, granodioritic, and syenitic masses, which have also been provisionally grouped together, though they are of more than one age. Granite pebbles in some of the folded conglomerates show there is (or was) older granite in the vicinity, but it has not yet been recognized. The youngest consolidated rocks are a series of flat-lying sandstones and conglomerates.

One hundred miles to the north there is the Coppermine River Series of gently dipping sandstones, shales, conglomerates and basaltic flows. These two formations may possibly be correlated. The basic dikes and sills are grouped together as they have not yet been studied. They, and the quartz veins, cut the flat-lying sandstones and all the other rocks, but their relations to each other are unknown.

The oldest rock group extends for 6 miles south, and 40 miles north, of the vicinity of the pitchblende and silver deposits. West of these rocks, for 20 miles north of the deposits, on the islands that fringe the coastline, granitic rocks are exposed. The flat-lying sandstones are found 40 miles north of the deposits and extend for an unknown distance north and west. The basic dikes and sills are widespread and individual bodies may have great length. The quartz veins are of great size and length. They are found in a belt several miles in width which has been traced for 60 miles in a N.N.E. direction.

PITCHBLENDE-SILVER DEPOSITS.

General.—At the original discovery point, pitchblende with associated native silver has been found. Silver deposits (without pitchblende) have been found 6 miles south and 1¼ miles N.E. of the original discovery. Six miles S.E. and 2 miles N.E. other pitchblende discoveries have been reported. The last two localities have not been examined.

The deposits examined occur in combined shear and shatter zones in folded sediments and volcanics, commonly within a mile of their contact with intrusive granite.

LaBine Point Deposits.

Areal-Geology.—At LaBine point, the site of the original discovery, are fine-grained banded sediments, volcanic agglomerate, and perhaps some flows, all now metamorphosed by granite which lies along the west side of the point. A basic sill up to 200 feet thick intrudes the sediments and volcanics, and outcrops on the island at the south end of the point, and on the next point to the east, one-quarter mile away (Fig. 1). It occurs again on the lake shore 1¼ miles north of the point. One thin section from this last locality shows plagioclase (andesine-labradorite), enstatite, biotite, and quartz as the major constituents, and the rock has the composition of a quartz norite. The granite has caused baking and granitization of the sediments to such an extent that over large areas the bedding has been completely obliterated and a

mottled pink and greenish gray massive fine-grained rock has resulted. Examination of thin sections of these rocks shows a mass of tiny interlocking grains, commonly sodic plagioclase, but in some instances quartz. In places, the grains are irregular in size and do not always interlock. In most sections examined secondary magnetite and green or brown biotite are present. Other minerals identified are chlorite, epidote, garnet (probably grossularite), carbonate, and in one section, albite in a veinlet. The stages in the metamorphism have not been determined. Magnetite is particularly widely distributed in the rocks of the point. Disseminated pyrite occurs in places, and weathering has yielded large gossans in which limonite and gypsum are abundant.

Structure.—Sufficient remains of the bedding of these rocks to show that there is a general N–S strike and moderate westerly dip, with numerous local variations. The sill intruding these rocks on the island at the south end of the point dips to the southwest, whereas on the next point one-quarter mile east, it dips to the east. The intervening bay apparently is an anticlinal axis.

Shear Zones.—Three main shatter and shear zones have been found at Labine point striking in a general E.N.E. direction and converging somewhat in that direction (Fig. 2). A second set of fractures also shown on the map trends 40° west of the main zones, and there are small veins in various directions. All three zones dip steeply to the N.W. The hanging or N.W. wall is commonly visible in natural exposures, the other edge is mostly concealed by a drift-filled depression or by the lake. In many instances the N–S fissures and veins do not intersect the main shear zones but rather branch out from them. In one case, at the south end of the middle (No. 2) zone, a cross vein intersects the zone, but there is little, if any, displacement.

The three main zones on the point have been numbered 1, 2, and 3 from S.E to N.W. The width of the shattering is irregular and ranges from one foot up to 50 feet. The No. 1 zone has been traced for 1000 feet in length with a possible extension of 1200 feet to the north and 1400 feet to the south. The No. 2 zone has been traced nearly continuously for 1400 feet from the

lake shore to a small pond under which it disappears. The pond and a small swamp extend along the strike for 1200 feet and in the exposures beyond this the zone is not recognized. The No. 3 zone has been traced from the lake shore for 600 feet, beyond which it has not been definitely recognized. These shatter zones

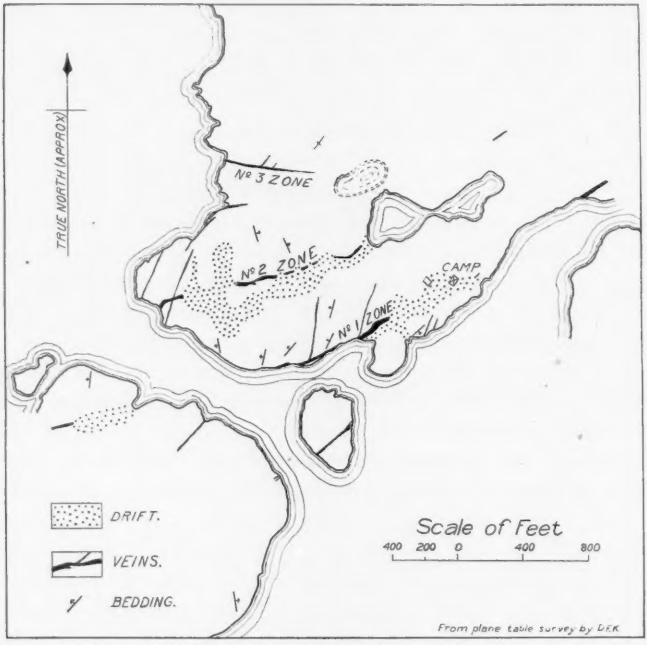

FIG. 2. Map of pitchblende-silver deposits, LaBine Point, Great Bear Lake.

have been the seat of repeated movement and the loci of mineralization.

In the middle (No. 2) zone the metamorphism by the granite has been more intense than in the adjacent rocks. Magnetite, coarse biotite, actinolite, and chlorite are extensively developed.

In the three major zones quartz has been introduced cementing

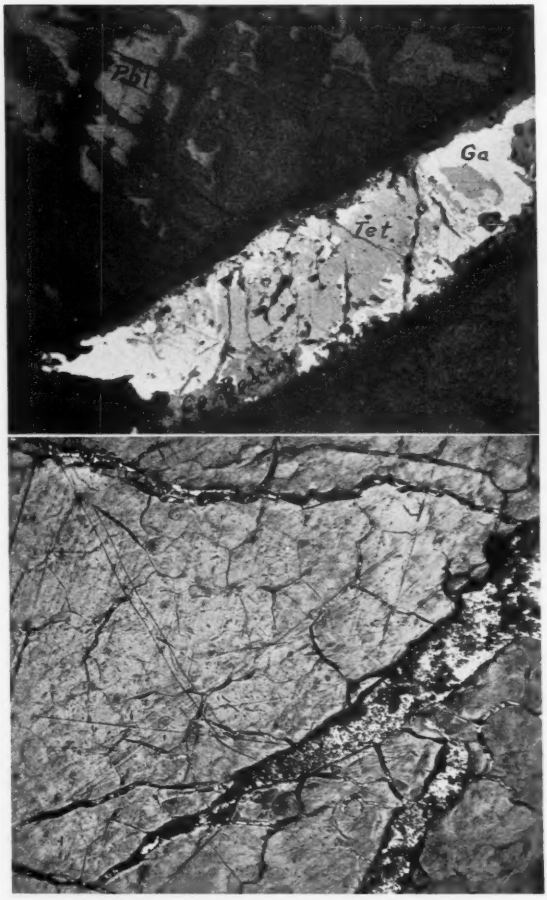

FIG. 3. (Top) Portion of seam of pitchblende showing a fracture containing galena (*Ga*), tetrahedrite (*Tet*), chalcopyrite (*Cp*), covellite (*Cov*) and a selvage of a carbonate mineral. The pitchblende (*Pbl*) is partially replaced by other material not identified. ×77.

FIG. 4. (Bottom) Shrinkage (?) cracks in pitchblende, the larger ones containing chalcopyrite, bornite, covellite and a carbonate mineral. ×77.

a breccia of country rock, or forming a stockwork where the movement of the rocks has not been so extensive. In the 1st and 3d zones it is the main filling. In the middle zone it is less prominent, particularly in the northern part of the zone. Specular hematite and a light brown or yellow iron-bearing carbonate are abundant in places in the No. 1 zone. Dark brown siderite is present at a number of places.

Metallic Minerals of the Deposit.—1. Pitchblende occurs as narrow seams, as colloform masses, and as brecciated fragments. The seams are from ⅛ inch to 1 inch in width, remarkably persistent, and though sinuous, are roughly parallel; several may occur in a foot or less width across their strike. Their walls exhibit typical mamillary or botryoidal structures which are radially fractured, the fractures being filled with later-formed minerals (Fig. 3). In places, what appear to be definite shrinkage cracks also contain later-formed minerals (Fig. 4). Polished surfaces show that some of the material forming the pitchblende seams is not homogeneous, but that it consists of a gray mineral with a smooth surface, probably pitchblende, partially replaced by a somewhat softer and apparently porous substance which has not yet been identified (Fig. 3).

Homogeneous pitchblende in colloform structures is present in the southern part of No. 2 zone, "globulina-like" forms being found in a matrix of quartz. This pitchblende shows definite radial fractures which have been filled with later minerals (Fig. 5).

The third manner of occurrence is as a breccia of angular fragments of homogeneous pitchblende cemented by quartz. The outlines of many of these fragments are crescent shaped or segments of rings, showing clearly that they are parts of the "globulina-like" forms referred to above (Fig. 6).

2. Arsenopyrite is present in a quartz vein up to 2 feet wide branching from the No. 1 zone. It has angular boundaries against pyrite and is much earlier than chalcopyrite and sphalerite. It is also found as scattered grains in the north end of the No. 2 zone.

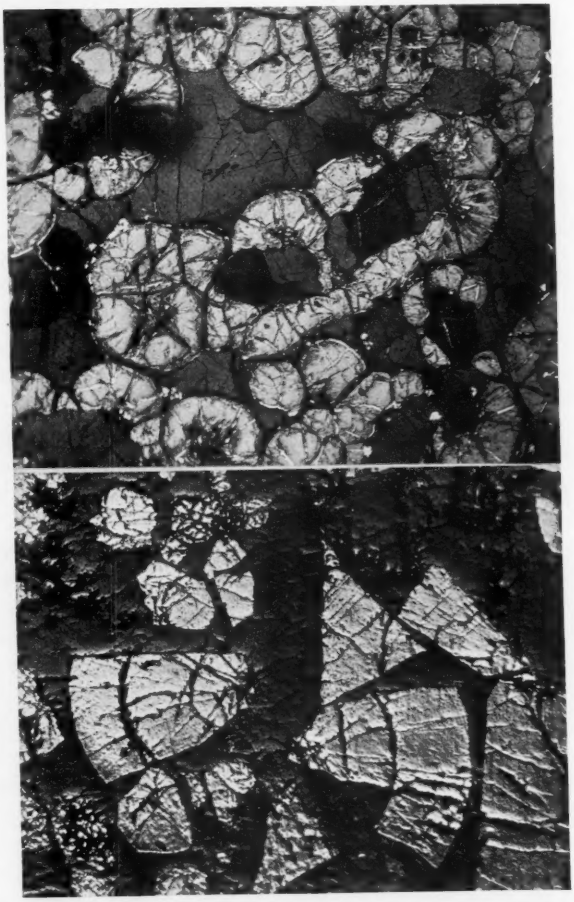

FIG. 5 (top). Colloform structures in pitchblende (light) in a quartz gangue. Borders of pitchblende and cracks contain covellite and Mineral A. ×80.

FIG. 6 (bottom). Angular fragments of pitchblende (light) cemented by quartz (dark). The segmental character of some of the fragments shows that they are parts of colloform structures similar to Fig. 5. ×13.

3. *Pyrite* is found as clusters of residual grains in chalcopyrite from many parts of No. 1 and No. 2 zones. It occurs with arsenopyrite as noted above. In places it is abundantly disseminated in the altered rocks of the shear zones.

4. *Tetrahedrite* has been identified in microscopic amounts in many specimens from the No. 2 zone. It occurs associated with galena and sphalerite. At one place it is cut by veinlets of chalcopyrite.

5. *Sphalerite* has been identified in several specimens from different parts of the No. 2 zone, and as noted under arsenopyrite. Its usual association is noted under tetrahedrite.

6. *Bornite* is widespread but is not abundant. It is present at a number of places in the No. 2 zone. It is partially replaced by chalcopyrite, but at one place a regular pattern of chalcopyrite needles is present in the bornite. It is found in cracks in pitchblende, and with chalcopyrite and galena. In a narrow shear zone traversing an islet on the S.E. side of the point ("island zone"), it is found associated with cobalt-nickel minerals. It forms cores (perhaps replacement) surrounded by concentric rings of the cobalt-nickel minerals, and can be seen in the same specimen with chalcopyrite in later veinlets cutting the cobalt-nickel minerals.

7. *Chalcopyrite* is widespread and at least two generations are present. In the southern part of the No. 2 zone it occurs in places disseminated with steel galena and magnetite. In the No. 1 zone it occurs as massive lenses replacing pyrite. It is found in fractures in pitchblende (Fig. 3), in places partially replacing it (Fig. 8). A later generation forms crystals on crystals of quartz lining the walls of veinlets.

8. *Galena* is widespread in the No. 2 zone but is not as abundant as chalcopyrite. It has been identified at one point in the No. 1 zone. It occurs in cracks in pitchblende. Its other associations have been noted above.

9. *Cobalt-nickel minerals.*—Several hard white minerals belonging to this group have been found. The commonest of these minerals occurs as selvages along the edges of certain late veinlets

in all three zones. It is isotropic or only faintly anisotropic and contains cobalt, nickel, iron, and arsenic. This mineral is traversed by veinlets of a different mineral visible only after etching with conc. HNO_3 to which the second mineral is negative. The second may be cobaltite.[2]

In one specimen from the "island zone" (see under bornite) at least two other minerals of this group are present. They are almost exactly the same in color and are strongly anisotropic. They occur as rude spherules in quartz. Etching with 3:7 HNO_3 leaves one of these minerals unaffected and shows that in places it forms concentric rings around the spherules. This mineral is etched by Conc. HNO_3. The mineral that etches with dilute HNO_3 has the etch reactions and some of the other properties of rammelsbergite. Work is in progress to determine these various minerals.

In another specimen from the "island zone" remarkable fern-like structures in a hard white isotropic mineral of this group have developed (Fig. 9). In some cases the interiors of these structures contain native bismuth (Fig. 10).

10. Native bismuth has so far always been found associated with the cobalt and nickel minerals. It is widespread in small amounts.

11. Argentite, associated with covellite, tetrahedrite, and galena, has been identified under the microscope in a single specimen from the north end of the No. 2 zone.

12. Covellite is widespread in small amounts. It is present in fissures or cracks near other copper minerals.

13. Native copper has been seen as a few tiny specks in the No. 2 zone. The relations are unknown.

14. Native silver is abundant in places in the northern part of the No. 2 zone and in smaller amounts at other places in this zone, at one spot in the "island zone," and in two other small veins on the property. Where abundant, it is associated with a reddish brown manganese-bearing carbonate. In the southern part of

[2] H. V. Ellsworth has since identified this material as skutterudite occurring in zonal intergrowths with, and around cores of, earlier smaltite-chloanthite. The skutterudite probably contains isomorphous nickel skutterudite.

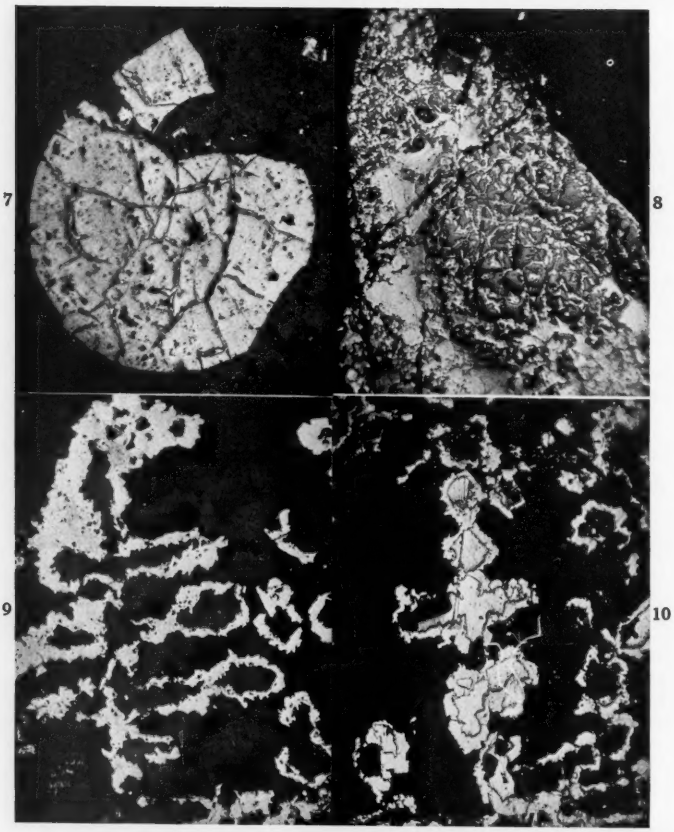

FIG. 7. Partially brecciated spherule of pitchblende in quartz. The cracks hold chalcopyrite. × 22.

FIG. 8. Part of angular fragment of pitchblende in quartz gangue (black). Pitchblende (gray, in relief) is partially replaced by chalcopyrite (white). × 52.

FIG. 9. Fern-like structures in a hard white isotropic cobalt-nickel group mineral. The gangue is carbonate. × 32.

FIG. 10. Same mineral as Fig. 9, only centers of structures are filled with native bismuth. × 32.

the No. 2 zone it is associated with galena and chalcopyrite. At this locality the silver is later than the galena. It is found as (1) a mass of wires in a manganese carbonate gangue, (2) plates and leaves, in some places with the carbonate, between the surfaces of botryoidal slabs of pitchblende, in places holding the pitchblende together, and (3) as plates in fractures, and as tiny wires disseminated through, only slightly fractured country rock.

15. Mineral A.—This unknown mineral is strongly anisotropic (blue to brown), color pale bluish gray, almost exactly like tetrahedrite, brightness about the same as tetrahedrite, hardness C. Its etch reactions are: HNO_3—neg.; HCl—neg.; KCN—doubtful; $FeCl_3$—pos., tarnishes irid.; KOH—light brown irid. tarnish; $HgCl_2$—slight tarnish. It occurs as veinlets cutting pitchblende, in cracks in pitchblende (Fig. 5) and invading tetrahedrite. It is often intimately associated with covellite.

16. Mineral B.—This unknown mineral is strongly anisotropic, color slightly darker gray than tetrahedrite, hardness C. Its etch reactions are: HNO_3—stains irid.; HCl—doubtful; KCN—turns black, deeply pitted; $FeCl_3$—turns brown, then etches deeply. It occurs as tiny, highly irregular grains in tetrahedrite.

General Relations of the Important Minerals.—Pitchblende was among the earliest minerals introduced. It occurs at most places on the hanging-wall side of the fracturing and in some places there has been some movement subsequent to its emplacement. Where it occurs intimately mixed with quartz the mixture forms massive lenses up to 60 cm. wide and several meters long. These tend to occur where there are slight changes in strike in the zone. In the No. 2 zone, where it has colloform structures in quartz, it must be of contemporary age. Where it is brecciated and cemented by quartz (Fig. 6) it is older. In some specimens from the No. 2 zone fragments of pitchblende have been partially replaced by quartz which in turn has been replaced by chalcopyrite (Fig. 8). In the No. 3 zone a narrow band of shearing borders the footwall of a massive 6-foot breccia vein of country rock and quartz, and in this shear zone is a remarkably persistent ½ inch seam of pitchblende. In this case it appears to be somewhat later than the quartz of the breccia. Pyrite, arsenopyrite, bornite,

tetrahedrite, sphalerite, chalcopyrite, galena, covellite and native silver are all later than pitchblende and most of them have been found in cracks in it. Their relations to each other, where known, have been detailed above under the separate minerals.

In all three zones and in some other fissures, a rather definite mineralization stage of cobalt-nickel minerals, chalcopyrite, native bismuth, quartz, and an iron-bearing carbonate (ankerite?) is found. It consists of narrow, sharply defined fissures up to a few inches wide with a selvage of cobalt-nickel minerals on which are grown quartz crystals, on which, in turn, there may be crystals of chalcopyrite. In places these line a vug, but commonly the cavity is filled with the carbonate, in which are scattered grains of native bismuth. This mineralization stage is quite definite, the only variation noted being a reversal of the quartz and the cobalt-nickel minerals at one place. The exact position of this stage in the mineralization sequence is not known. In the No. 3 zone, one of these veinlets cuts the pitchblende, and in the other zones the definite walls and commonly partial filling show its comparatively late development.

Surface Alteration.—The district has been glaciated, and although surface alteration of the deposit is intensive, it does not appear to extend to great depths. Even in the bottom of shallow test pits it is notably less. Alteration products of pitchblende are present as prominent orange and canary-yellow stains. Some green stains may be secondary copper-uranium minerals. The copper minerals have altered to azurite and malachite. The cobalt-nickel minerals have altered to erythrite and an apple-green stain which may be annabergite. The manganese carbonate has altered to a mass of sooty and clinkery alteration products. A secondary dark gray mineral seen in polished surfaces growing out as spikes from cleavage cracks in galena is possibly cerussite.

Source of the Mineralization.—The adjacent granite or its parent rock is the most obvious apparent source of the mineralization.

The LaBine Point deposit and the other silver deposits of the district lie in shatter and shear zones in rocks adjacent to their contact with intrusive granite. The basic sill at this locality and

similar basic dikes and sills in the region were searched for important fissures, shear and fracture zones, and quartz veins, and none were found. It seems safe to conclude that the major movements in the shear zones at LaBine Point were earlier than the introduction of the sill. The silver, however, is a late mineral in the deposit, so the sill or its parent rock cannot yet be eliminated with certainty as a possible source of that part of the mineralization. The combination of a basic sill and an adjacent deposit of native silver is an attractive basis for suggesting a deposit of the Cobalt type. The present study indicates, in the opinion of the writer, that this is, as far as he knows, a new type of silver deposit for Canada. The association of pitchblende, native silver and other silver minerals, with copper, lead, zinc, nickel, cobalt, bismuth, and manganese minerals bears a resemblance to some of the deposits of the Erzegebirge in Germany and Czecho-Slovakia, as has already been in some degree pointed out.[3] Little analogy with Cobalt can be drawn.

SUMMARY.

1. Pitchblende and native silver have been found at several localities in an area seven miles in diameter.

2. They occur in shatter and shear zones cutting altered rocks near their contact with intrusive granitic rocks.

3. A variety of minerals are present and among their elements are uranium, copper, lead, zinc, nickel, cobalt, arsenic, bismuth, silver and manganese.

4. The pitchblende exhibits colloform structures and is a very early-formed mineral in the deposit.

5. The deposit described in detail resembles more closely the silver deposits of the Erzegebirge than those of Cobalt.

In conclusion grateful acknowledgement is made to Professor Edward Sampson for placing at the writer's disposal the facilities of the Department of Geology, Princeton University, and for valuable advice and criticism in the preparation of this report.

GEOLOGICAL SURVEY,
OTTAWA, CANADA.

[3] Knight, Cyril W.: "Pitchblende at Great Bear Lake." Can. Min. Jour., vol. 51, no. 41, Oct. 10, 1930, p. 964.

EARLY DISCOVERIES OF PETROLEUM IN THE UNITED STATES.[1]

H. B. GOODRICH.

INTRODUCTION.

AMONG the numerous contributions on the subject of petroleum history are most interesting ones by M. R. Campbell, Ralph Arnold, E. L. DeGolyer, Sidney Powers and J. V. Howell. The ground has been well covered, but it is thought that, notwithstanding the wealth of literature, some points have not yet been emphasized fully enough. From the human interest viewpoint there are still some facts of the past that might repay further consideration and help in an ultimate analysis of petroleum geology.

If such a study seems worth while, it is suggested that one reread Lord Macaulay's critical "Essay on History" published in 1828. That author warns of many pitfalls in the path of the historian. Although one realizes that he uses the following only to illustrate one of his points, it is startling when one runs across it. I quote:

> Bishop Watson compares a geologist to a gnat, mounted on an elephant, and laying down theories as to the whole internal structure of the vast animal from the phenomena of the hide.

Macaulay, fairly enough, notes that the comparison is unjust even to his geologists of one hundred years ago; although he could not have foreseen how much deeper into the hide the swarm of 1931 geologists might be able to look with the aid of subsurface work and geophysicists.

But a more serious thought of his has a bearing on the history of petroleum geology. I quote:

> No past event has any intrinsic importance. The knowledge of it is

[1] Presented before the joint session of the Society of Economic Geologists and the American Association of Petroleum Geologists, Tulsa, Okla., Meeting, Dec. 30, 1931.

valuable only as it leads us to form just calculations with respect to the future.

Although there had been oil production in small amounts previously in Texas, the Spindle Top gusher was brought in thirty one years ago. Those who were not present in those hectic times will receive a thrill if they will read the contemporary comments. Note the progress of Captain Anthony F. Lucas, a mining engineer, who argued from his own sulphur well drilling experience, that there might be oil on the mound south of Beaumont. His knowledge of salt domes could not have been great in advance of any development. However, first against considerable financial opposition, and later with some assistance, he persevered. Making practical improvements on the toy-like rotary drilling rig of the day, he completed the hole; and, literally, astonished the world with the Lucas Gusher. I am convinced that this well had the largest initial production of any that has ever been drilled in the United States, although of that some doubt has been expressed. Captain Lucas once said that he felt fully repaid for all his trials by the mere fact that his discovery had opened up such wide opportunities for thousands of oil men in the unknown Southwest, many of whom came to and were builders of this city of Tulsa. And geology has benefited enormously by the Salt Dome literature to which that discovery led.

Spindle Top is one out of thousands of happenings in our own oil generation, whose historic facts are of accessible record. But even in such modern incidents diverse personal memories and opinions arise to influence our individual interpretations and evaluations of those facts. When one considers the more distant clouded past, such differences of interpretation multiply.

In this discussion it may seem unorthodox to dispute the often repeated statement that Colonel Drake's well near Titusville, Pennsylvania, in 1859, was the first discovery of petroleum in the United States. However, the fact is that whenever that statement is made, its author proceeds to qualify it. Therefore, without any wish to disparage Drake's great achievement, it is here suggested that petroleum history in the United States should be divided into two periods.

The first one dates back to the aborigines, before the arrival of the white man, and continued on to 1859. It was characterized by an appreciation of petroleum as an article of value, filling many of the limited, but slowly advancing, requirements of an adolescent humanity. Accepted as a gift from the Almighty, oil was recovered from its natural seepages, or as a by-product of water-well flowage. There were but slight incentives for developing more abundant sources.

Through the 1840's and '50's civilization's demand for better illumination became imperative. Responding to this came inventions and chemical research that prompted the Drake wildcat well, and ushered in the second period of developments, to supply the growing market.

The first period, then, was one of generally unpremeditated discoveries; the second became one of intentional discoveries.

DISCOVERY.

A discoverer is one who first brings something of value to the knowledge of the civilized world. Recognition of its value may be immediate or delayed. Lief Ericsson was a pioneer only. But Columbus was the real discoverer of the New Continent, because (even though he may have thought it was India) he brought it to the civilized human view. Following the parallel, the American Indians, whose ancient oil seepage operations were found by the earliest settlers in the Alleghanies, were only pioneers. So also were the white men who collected oil from springs and used it for home remedies. But when a man went out and dug a hole, shaft, or well, and by his labor found a previously unrecognized source of oil or gas, he added to human knowledge and wealth, and earned discovery honors. It does not seem necessary that he should have started the hole in the ground expressly for the purpose of obtaining hydrocarbons.

In this first period, before 1859, were discoveries most of which were accidental.

THE FIRST PERIOD.

Apparently I. C. White of the West Virginia Survey did not make this same arbitrary distinction between the pioneer and the discoverer. In an historical summary[2] he shows that in the Great Kanawha Valley, near Charleston, W. Va., were the first salt works in the United States. In search for salt, the Ruffner brothers bored the first well west of the Alleghanies in 1808, and started the well-drilling business in the United States upon which the oil industry of today depends. Nearly all the wells there contained petroleum, estimated at 25 to 50 bbls. per day. It is a question whether that by-product of wells competed with the oil collected by trenching on seepages and sold in the local markets. Nor is it quite clear that White is justified in the claim that all discoveries, not only of mechanics of drilling, but also of oil production, originated in West Virginia and antedated those of the State of Ohio by fifteen years. Certain it is that, in 1814, a well bored for salt on Duck Creek, near Marietta, Ohio, to a depth of 475 feet, furnished petroleum that was sold and in part used for lighting. Dr. S. P. Hildreth, writing in 1833, is the authority for this. You will recall that Hildreth was the first geologist of the Ohio Valley, more than one hundred years ago.

He states, "the oil from this well is discharged periodically with great quantities of gas." After years of thus flowing by heads, the output, in 1833, had diminished to about a barrel per week, which was worth, at the well, 50 to 75 cents per gallon. In another place Hildreth stated that oil from the Kanawha had been used as an illuminant after filtering through charcoal to remove its empyreumatic odors, and he ventured the prophecy that in Ohio, petroleum would be used to give a "clear brisk light in lamps of future cities of the State." He had some advanced ideas also about natural gas in that connection. Furthermore, the value of petroleum as a lubricant was recognized. The production near Marietta was stored. Storage oil was once carelessly ignited, so that they had an oil fire.

In other words, as the result of a discovery of oil and gas in

[2] W. Virginia Geol. Survey Ann. Rep., 1899, vol. I.

1814, commercial production was established. On an infinitesimal scale, in the first quarter of the nineteenth century they had run the gamut of experiences which, magnified thousands of times, well drillers and operators of today have gone through.

Without recounting the interesting conjectures and gossipy stories of that first period, I will give here only a tentative skeletal chronology of oil and gas prior to 1859 in the order of historical rank.

First Rank, E. Ohio.

1814. 475-foot well, Duck Creek. The product marketed.

Second, West Va.

1815. Wilson's gas well, Charleston. Uncertain whether used. Commercial seepage at Burning Spring, Kanawha.

1841. Tompkins gas well at Kanawha, used for fuel.

1843. Dickinson, boring for salt at 1000 feet. Gas used as expulsive and conveying agent for brine and as operating fuel for salt making.

1844 to 1860. Sales of oil. See Creel; at Hughes river to the Bosworth Co. at 33 to 40 cents per Gal. 397 bbls. sold from 1847 to 1855.

Third, New York.

1821. Fredonia well, 27 feet deep. Gas for thirty burners lighting the town. See Lafayette's visit in 1824.

1851. Barcelona. Gas-spring excavated supplied a lighthouse.

1858. Fredonia. Under original well two wells, 100 and 150 feet, bored.

Fourth, Kentucky.

1819. Beatty well, McCreary County, large flowing well, possibly all oil wasted.

1829. Burkesville well, American well, Cumberland County. Large well flowed for years. Some oil marketed, mainly for medicine.

1840. Near Barbourville, S.E.Ky. First oil.

Fifth, Western Ohio.

1836. Findlay. First gas in Williamson well, ten feet deep.

1838. Findlay. Gas from well conveyed to Foster's residence. Used many years. First domestic use. Re-discovery years later.

Sixth, Pennsylvania.

1845. (?) Near Tarentum; Peterson began sale of 2 bbls. per week from his well for lubricant.

1853. Commercial oil from seepage, Venango County.
1859. The Drake well began present development.

Here ends the first period and begins the second period, that of intentional discoveries.

THE SECOND PERIOD.

History is a tricky, elusive subject. One would think that with the compilation of statistics since 1859, facts would be self-evident; but bare figures are often deceptive.

In the early days of the oil business, no doubt producers were too much occupied in caring for floods of oil to pay attention to production statistics. Figures collected were unavoidably inaccurate. With the advent of pipe lines about 1876, production accounting became more efficient. In 1883 the U. S. Geological Survey began the annual publication of "Mineral Resources" which contains chapters on Petroleum and Natural gas. Attention is called to the Tables of Production from 1859 on, appearing in each of these reports; but particularly to those of 1904 and 1905.

The Petroleum Chapter was compiled in 1904 by F. H. Oliphant, and the production table includes the following notes:

New York and Pennsylvania grouped together, beginning in 1859, are carried through to the current year.

Ohio	produced	before	1876	200,000	Bbls.
West Virginia	"	"	"	3,000,000	"
California	"	"	"	175,000	"
Kentucky and Tennessee	"	"	1883	160,000	"

Total produced but not allocated by years 3,535,933 Bbls. The above is included in the grand total U. S. production as of 1904; namely 1,382,815,000 barrels.

There is a further notation of an estimated thirteen and a half million barrels, wasted and not sold; but this need not concern us.

The 1905 Petroleum Chapter was in charge of W. T. Griswold, who introduces the Production table as follows:

In the previous publications of this table an estimated number of

barrels has been entered in the production from a number of States for the time prior to the date of collecting current statistics; these quantities have been omitted from the table as now published.

They have been so omitted ever since, in the amount of three and a half million barrels. This explanation only, appears:

It is reasonable to suppose that the estimates dropped in 1905 were then found to be either too inaccurate or too mythical to warrant perpetuation as records of actual production.

There is no doubt that the Government statisticians had reasons, satisfactory to themselves but not apparent to the layman, for suddenly cutting out production figures that had been carried on record successively for nineteen years. Indeed the amount of three and a half million barrels makes no appreciable difference in the United States grand total of say thirteen billion barrels up to 1932. From the accountancy viewpoint any such small difference may be ignored. However, it is suggested that the casual reader of any of the statements of production issued before 1905 has an entirely different perspective than he who relies upon subsequent statistics. The main point is that, although those prior production figures are admittedly inaccurate, still there is an implied "myth" in their suppression. For, now, according to later authoritative statements one would logically assume the misleading conception that certain States produced no oil before 1876 and 1883.

In general, none of the dates of initial production should be accepted unquestioningly, but should be subjected to verification by contemporaneous (even if unpublished) testimony because until oil from discoveries is marketed, the statistician generally lacks official data. A local case in point was a successful wildcat in Oklahoma in 1905. The date is important only because, from it, geologists started to pay attention to possibilities in a region that had not been promising. Later, the district became most interesting. I refer to the remarkable scientific and economic discoveries of the modern geologists in the region south of the Arbuckle mountains. The small output of that particular

wildcat well was not marketed for a long time, and it is doubted that it ever found a place in official statistics.

The States that are credited with no production in the early years are Ohio, West Virginia, Kentucky, Tennessee, and California.

As to California, Arnold and Kremnitzer state that even before the Drake well, namely, in 1857, the Dryden well, in Los Angeles, was bailed and a few barrels sold to a refinery; that, in 1861, there was a small refinery in Ventura.[3] From other sources it appears that during the 60's in the State there had been one unfavorable report, but another, a chemist, had reported favorably. Scientists were active. Oil was mined and wells were drilled. In 1865 there were 50 wells in Humboldt county and a production of 1200 bbls. for California. There was a time of inactivity but a revival in 1875. The truth is that California was oil-minded immediately after the Pennsylvania start in the Second Period, and was one of the earliest in the producing list.

As to Ohio, the Macksburg discovery was in 1860; Cow Run came in 1861. Minshall and others give statistics of actual production, transported in the first years of that blank period, by wagon and steamer, to a total much greater than the omitted 200,000 barrels.

In West Virginia, production that was brought in immediately after the Drake Well was practically abandoned during the Civil War, but was resumed in 1865 and carried on.

In Kentucky, which is ignored prior to 1883, near Barbourville, oil which had been known since 1840 was drilled for in 1867 and there was a flowing well at a depth of 400 feet.

In Tennessee, there were 13 wells in Overton County in 1866–67. The Newman well was reported to yield 2600 barrels. Shipment of 5000 barrels to Nashville was also reported.

As already stated, it is not maintained that figures omitted for the first time in the 1905 U. S. tables were accurate. It *is* contended that the impression conveyed to the contemporary reader by their omission, is erroneous. The same idea applies to many

[3] Petroleum in the United States and Possessions (1931), pp. 740 and 775.

other of the State groups. For one instance only, Colorado first appears in the table in 1887. In 1862–65 there were some small wells northeast of Canyon, and the oil was shipped to Denver, where it was used for illuminating purposes, and it is stated that up to 1870 three thousand gallons had been sold. Considerable development and some successes are reported in Colorado in the early 80's.

It is hoped that nothing in these remarks will be construed as an attempt to criticize the conscientious work of statisticians. The endeavor has been to present a few notes that throw light on the early development of the petroleum industry and petroleum geology. Petroleum has a commercial history dating back further than many people take time to realize. In calling attention to a few of its old milestones, it is suggested that from the beginning, geologists have played an important part. Along with the industry, pure geology has grown and the petroleum geologist of today should have pride in a worthy inheritance that comes through, not seventy-two years, but more than one hundred, of this country's history.

1628 S. Cincinnati Avenue,
Tulsa, Okla.

CHRYSOTILE ASBESTOS: I, CHRYSOTILE VEINS.[1]

STANTON B. KEITH AND GEO. W. BAIN.

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INTRODUCTION.

CHRYSOTILE deposits described in this paper occur in the Missisquoi Valley in north-central Vermont and on or near Belvidere Mt. (Fig. 1). Hyde Park on the St. Johnsbury and Lake Champlain R. R. and North Troy on the Canadian Pacific Ry. are the closest rail points; Belvidere Mt. itself is accessible only by auto. The quarry of the Vermont Asbestos Corporation, on

[1] To be followed in the next number by an accompanying paper on "Chrysotile Solutions," by Geo. W. Bain.

the south side of the mountain, is reached by road from Eden Mills. Pits of the old Gallagher quarry on the northeastern side, at the eastern end of the same serpentine mass as the southern quarries, are accessible by roads from Lowell and Eden.

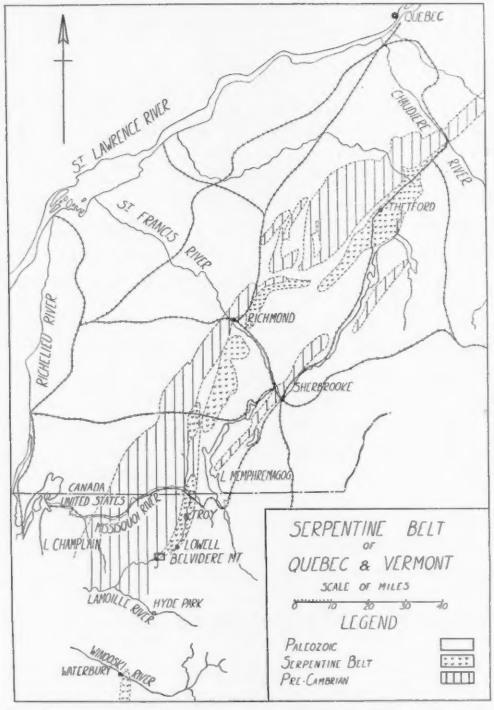

FIG. 1. Map showing location of serpentine belt in northern Vermont and southern Quebec.

General Geologic Associations of the Deposits.

Serpentine bodies in the Missisquoi River Valley are oriented principally north and south. The Serpentine Belt is in contact on the west with a gneiss or banded granitic rock which is the backbone of the Green Mountains. Graphitoid slate on its east

flank has been intruded by a number of small lenses and stocks of granite. Black graphitic gneiss, chlorite schist, and amphibolite lie between these bordering bands and are intruded by serpentine and dunite containing the chrysotile deposits.

Summary of Previous Work.

General Associations of Chrysotile.—The majority of chrysotile deposits occur in partially serpentinized peridotite, dunite, or pyroxenite.[2] The well known deposits of Thetford and Black Lake, Quebec, and of Vermont belong to this type, being found in incompletely serpentinized peridotite. The serpentine is found near the sides of serpentines that extend due south from Eastman, Quebec; both sides of the lenses seem to be sheared, fractured and serpentinized. Previous studies of deposits were conducted in the Quebec districts and the present study is devoted principally to the Vermont deposits.

Theories of Vein Formation.—Cirkel[3] was the first to make a complete study of the formation of the chrysotile in this belt. He believed primary fracturing to be due to gradual alteration of olivine intrusives to serpentine through hydration, the increase in volume causing slow readjustment of the rock masses. Later shrinkage caused additional fissuring in which asbestos formed, due to infiltration of serpentine solutions from segregations and later slow crystallization of this solution.

Dresser[4] and Graham,[5] however, do not consider these adjustments to be mechanically possible and believe the veins of chrysotile to be due in large measure to replacement or recrystallization of serpentine along joints or fractures. They point out that the crystals appear to have grown out from an original crevice into the walls and seem to be recrystallized portions of the walls themselves. These authors indicate a definite ratio of width of asbestos vein to a bordering serpentinized band. They dissent from Cirkel's conclusion in believing that the veins are formed by

[2] Diller, J. S.: U. S. Geol. Surv., Bull. 420, pp. 3–22.
[3] Cirkel, F.: Chrysotile Asbestos, Can. Mines Branch, 1910.
[4] Dresser, J. A.: Can. Geol. Surv., Mem. 22, 1913.
[5] Graham, R. P. D.: ECON. GEOL., vol. 12, p. 154, 1917.

infiltration of solutions into crevices which are enlarged by replacement, with fracturing both the cause and effect of serpentinization.

Taber [6] holds a different view and considers the chrysotile veins to be formed by crystal growth pushing the walls apart. The crystals grew from solutions introduced at their base.

Accordance of Salient Facts with Theories.

Three modes of chrysotile vein formation appear possible in the deposits studied.

1. Recrystallization of the material *in situ.*
2. Solution with short distance transportation followed by deposition in fissures.
3. Totally foreign origin or long distance transportation.

A characteristic of veins of the first type should be irregular or at least unmatched walls. Veins should become narrow or simple fractures across foreign or non-origin minerals or through impermeable stretches, and should show some relation to width of serpentinized wallrock. However, veins in many parts of Vermont lack wall alteration on either side; the walls commonly show complementary form characteristic of filled fissures, and split crystals and intersecting veins are offset approximately along the fiber direction. Also chrysotile formed by recrystallization of serpentine has a sheaf or a matted structure and the veins have irregular walls. Replacement is evident along the walls of a few veins but appears to be a minor factor.

Veins produced in the second manner should have matched walls with numerous local enlargements along them. Such veins should maintain fairly constant width across all materials and along the fissure sections should take on the form imparted by stress relief. Permeability would be of negligible importance except where the dissolved material originated. Evidence of extensive replacement enlargement could not be found although it may possibly occur.

[6] Taber, S.: Trans. A. I. M. E., vol. 57, p. 62, 1918.

Matched walls are common, even across inclusions, and indicate the possibility of total foreign origin or long distance transportation in solution, of materials to make chrysotile. The great number of offset wall structures along the veins would seem to indicate filled fractures. The majority of fillings take the form imparted by stress relief, and permeability is irrelevant to deposition of the veins; it shows up only in depth of serpentinization of the walls. Cirkel's theory is somewhat of this nature but the evidence seems to indicate definitely that the openings were produced by dynamic stresses and not by simple hydration expansion. It is difficult to imagine compound veins, so commonly found in this district, to be due to crystals of chrysotile pushing apart the walls as they grow. Single fiber veins with fibers extending from wall to wall would be expected.

The mode of formation of chrysotile veins in Vermont seems to differ so strongly from the generally accepted ones that it was decided to study the veins in detail. Relation of loci of vein formation to localization of stress directions in serpentine seemed to throw new light on the distribution of asbestos in a peridotite body. The possibility of a foreign source of the materials for vein filling and the origin of these materials also seems to afford definite grounds for expecting or not expecting chrysotile in a particular peridotite.

GENERAL GEOLOGY.

The chrysotile deposits occur in rocks of pre-Cambrian or early Paleozoic age along the east side of the Green Mountain geanticline. The Memphremagog limestones and slates of the Quebec group of distinctive Paleozoic age appear on their east flank. Thus, formations containing the deposits lie between definite Paleozoic sediments in a sinking area on the east and the pre-Cambrian gneiss and schist of a rising block on the west.

TABLE OF FORMATIONS.

Age.	Sedimentary Origin.	Igneous Origin.
Paleozoic.....	Lowell Mts. slate, phyllite and schist....	Granite.
	Quartzite and quartzite conglomerate....	Peridotite and serpentine.
		Belvidere Mt., amphibolite.
Pre-Cambrian..	Biotite schist	Chlorite schist and tuff.
	Sutton Mt. gneiss	Gneissoid granite.

Description of Formations.

Sutton Mountain Gneiss.—This light gray gneiss lies west of the serpentine belt and is an injection phase of the biotite schist of the same region. It possesses distinct banded structure and is greatly contorted locally. Dark bands are original biotite, light bands are injected quartz, orthoclase, and microcline; more rarely epidote is present.

Biotite Schist.—The rock along the Green Mountains is predominantly dark brown schist which has undergone slight injection. Numerous quartz and some feldspar eyes and stringers occur parallel to the schistosity. The formation is commonly much contorted; least metamorphosed phases are dark ottrelite biotite schist as on the west peak of Belvidere Mountain but in most of the territory it has been much more changed.

Gneissoid Granite.—Gneissoid granite outcrops near the crest of the Green Mountains and around Tillotson Peak. Oligoclase augen occur abundantly through it; intense fracture flowage, indicated by augen structure, is characteristic. Fine texture of the gneiss is due to its cataclastic structure.

Chlorite Schist.—This schist is found close to the Missisquoi Valley and is associated with serpentine and the Belvidere amphibolite. Epidotized fragments, resembling basaltic bombs, occur through the rock. Primary banding as well as secondary cleavage appear in it. Excellent tuff structure appears along the line of the copper mines south of Eastman, Quebec, and near the Roxbury verde antique quarry in Vermont. The formation seems to be metamorphosed volcanic tuff.

Belvidere Mountain Amphibolite. This rock is found from Belvidere Mountain as far north as the Hazen's Notch road. Exposures extend from the asbestos mine for 1000 feet to the top of the mountain and banding in it dips about 12° westward into the hillside. It is made of 35 per cent. dark blue-green amphibole, up to 0.1 inches thick and 0.25 inches long, and saussuritized plagioclase. It is a typical metamorphosed diabase or pyroxene diorite. Another body of this same rock outcrops between North Troy and Newport, just east of the Missisquoi.

Peridotite and Serpentine.—Peridotite and serpentine appear both east and west of the amphibolite on Belvidere Mountain and along either side of the Missisquoi Valley. The mass on the eastern side of Belvidere Mountain is intruded parallel to the banding of the amphibolite and dips under this formation. It possesses shear cleavage at the southwestern and northeastern ends. Otherwise it is massive except for local shear zones and cross fractures between them.

Quartzite and Quartzite Conglomerate.—Well stratified quartzite and quartzite conglomerate occur immediately east of the Missisquoi river at Troy and Westfield. Beds of pebbles up to ½ inch in diameter alternate with layers of fine quartzite and slate. Slaty cleavage crosses beds of quartzite and conglomerate alike.

Lowell Mountain Slate, Phyllite and Schist.—Fine-grained black to dark brown slates dominate in this group and occur east of the serpentine belt. Bedding is obscure; cleavage and jointed structures are characteristic. Schist is rare and occurs in a few places only. These rocks seem to correspond to the Quebec group on Lake Memphremagog.

Granite.—Small masses of medium-textured light gray granite cut the slates and serpentines at many places northeast of Lowell. Secondary structures are absent. The rock is extremely rich in anthophyllite where it is bounded by serpentine; yellow biotite is also very characteristic. Ferromagnesian minerals are abundant in most parts of it. The slates are slightly metamorphosed where this granite has cut them but serpentine in similar positions has undergone extensive alteration to talc.

Structural Elements.

Two structural elements are prominent in this region. One is the very old pre-Cambrian block, which has been a dominantly rising sector, and the other is the Memphremagog trough of Paleozoic age, which has been a sinking area. The serpentines lie along the borderline between these two elements.

Sutton Mountain–Green Mountain Geanticline.—This geanticline is an area of highly injected and intimately deformed pre-

Cambrian schist and gneiss. Materials were washed from this geanticline of early Paleozoic time, westward to fill the Taconic geosyncline and eastward into the Memphremagog trough. Serpentines lie along the edge of the rising block and have their greatest deformation along their borders. Commonly one border shows more deformation than the other.

Lowell Mountain Basin-Memphremagog Trough.—Younger pre-Cambrian and Paleozoic rocks dominate in this structural element. They are slightly injected but highly metamorphosed by mechanical processes. All but the very youngest granites have slaty cleavage. The serpentines are broken and sheared along the border of the geanticline. Movements on the fractures opened up the serpentine and asbestos deposits formed in the openings.

STRUCTURE OF THE SERPENTINE.

Major Structures.—The lens form of small serpentine intrusives at Roxbury and Rochester is controlled by the structure of the wallrock. The Duxbury talc deposit, near Moretown, plunges north and shows that the mile-long serpentine mass has a similar lens form. Similarity of small and large serpentine masses through Vermont might make it seem that those at Belvidere and Lowell would have the same form as these southern bodies. However, fracture cleavage in the peridotite and serpentine masses is the only apparent method of estimating their shape where mining and quarrying has not exposed their outlines.

Fracture Cleavage Structures.—Fracture cleavage in verde antique quarries at Roxbury, Rochester, and Moretown is indicated by a trellis of carbonate veins parallel to the length of a lens and dipping towards the walls of it. The obtuse angle between the fracture cleavage planes is controlled by the thickness of the lens, and the intersection of the planes is in the direction of the greatest length of the serpentine mass. This control of the fracture cleavage by the size and shape of the serpentine mass is illustrated by Table I.

TABLE I.

RELATION OF SIZE OF SERPENTINE TO FRACTURE CLEAVAGE ANGLE.

Serpentine Mass	Width	Inclination of Cleavages		Obtuse Angle
Roxbury No. 5	30 ft.	84° W.	84° W.	180°
Roxbury No. 2	45	63° 15′ W.	59° 15′ E.	122° 30′
Roxbury No. 6	60	73° W.	48° E.	121°
Stockbridge	180	45° W.	59° E.	104°
Roxbury No. 10	200	43° 15′ W.	57° E.	100° 15′
Rochester	400	45° W.	49° E.	94°
Moretown No. 2	850	Not measured.		90°

Note.—Fracture cleavage in Roxbury No. 5 corresponds to flow cleavage.

Two serpentine areas south of Waterbury, one in Duxbury, Fayston, and Moretown and the other in Fayston and Waitsfield, have fracture cleavage on a large scale. Cleavage planes in the Duxbury-Moretown mass intersect at 90° and the intersection pitches north at 30° or parallel to the pitch of the lens as measured in the Duxbury Talc mine. The Waitsfield lens and its fracture cleavage pitch north but the angle of inclination has not been measured becaused obvious absence of materials of economic value has discouraged mining work.

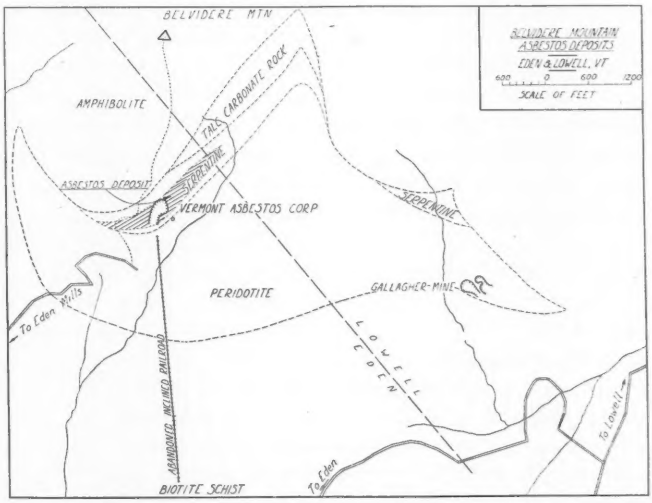

FIG. 2. Map showing extent of peridotite, serpentine and asbestos deposits on Belvidere Mt., Vt.

Evidence available indicates that fracture cleavage is parallel to the length of a serpentine mass. The pitch of the intersection of the two cleavages is the pitch of the axis of the serpentine, and the flow cleavage is parallel to its axial plane. The principal set of fracture cleavages in the east opening of the Gallagher mine on Belvidere Mountain (Fig. 2) strikes S. 7° E. and dips 43° W. A much weaker set strikes S. 80° E. and is vertical. Shear cleavage in the west opening strikes S. 35° E. to S. 50° E. and dips 77° S. Cleavage structures indicate that this serpentine mass might be expected to pitch downward to the northwest. Inclination of the amphibolite and schist walls indicate also that the intrusive pitches northward.

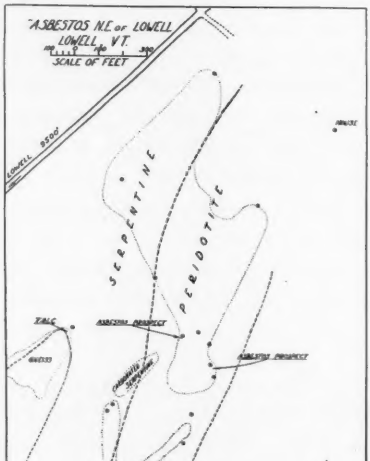

FIG. 3. Map showing location of asbestos prospects in peridotite and dunite northeast of Lowell, Vt.

A peridotite and serpentine body northeast of Lowell (Fig. 3) has three small asbestos prospects. One set of fracture cleavage zones strikes N. 56° E. to N. 67° E. and dips 78° N. to vertical. The second set of fracture cleavages strikes N. 16° W. to N. 16° E. and dips 45° to 55° W. A group of shear planes from 6 inches to four feet wide corresponds possibly to the flow cleavage and strikes N. 45° E. Joints and shear planes striking N. 50° W. occur near the south end of the peridotite. They are probably the N. 16° W. set of fracture cleavages disturbed by the local irregularity in the walls of the serpentine. The fracture cleavage of this serpentine mass indicates that its axis, and that of the asbestos bodies, pitches northwestward.

Peridotites in the vicinity of Belvidere and Lowell have the form of steeply inclined to nearly vertical phacoliths or sills. They lack the nearly perfect lens shape of the smaller southern masses. Nevertheless, the fracture cleavages and shear or flow cleavages have the same position relative to the axes of the intrusives as in the better exposed southern ones.

Shear Cleavage.—Shear cleavage in the large peridotite masses bears the same relation to fracture cleavage that flow cleavage bears in the small bodies. Shear cleavage is most common adjacent to the sides of large masses, especially around irregularities of the contact. Shear cleavage at the Vermont Asbestos Corporation mine strikes N. 53° E. and dips 50° W. This cleavage is approximately parallel to the banding in the amphibolite and to the axial plane of the Belvidere Mountain serpentine mass. Similar shear cleavage appears in the Lowell mass immediately north of the talc exposures.

Chrysotile Veins.—Chrysotile veins occupy neither fracture nor flow or shear cleavages. Veins in the east opening of the Gallagher mine have an average strike of S. 80° E. and are predominantly vertical. Veins in the western opening have an average strike of S. 70° E. and range in inclination from 59° N. to 61° S. The strike of these chrysotile veins is approximately parallel to the weaker fracture cleavage but the dip diverges widely. Veins show a drag along the principal cleavage and

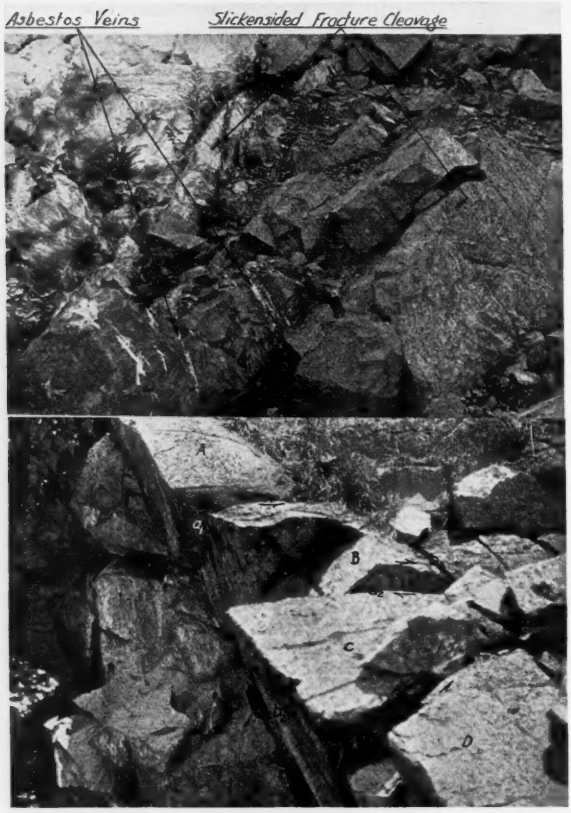

FIG. 4 (above). Photograph showing slickensided fracture cleavage in eastern Gallagher pit and asbestos veins crossing from one fracture cleavage to the adjacent one.

FIG. 5 (below). Photograph showing complex shifting of blocks along fracture cleavage planes in the prospect northeast of Lowell. Block *B* has shifted to the right relative to *A* and *C* along planes a_1 and a_2, which have offset fracture cleavage b_2. Block *D* has shifted right relative to *C* along fracture cleavage a_3.

seem to be due to torsion stresses in the blocks between the fracture cleavages (Fig. 4).

Chrysotile veins in the peridotite mass northeast of Lowell strike east and west where the principal fracture cleavage strikes approximately north and south. These veins dip at all angles as in the Gallagher deposit. The veins show drag structure adjacent to the principal fracture cleavage and have the form of torsion cracks.

Stresses Causing Fractures Containing Chrysotile.—Complex movement through the rock mass by continued crushing after development of fracture cleavage is regarded as responsible for the formation of the extremely irregular fissures that contain chrysotile. The general type of movement is illustrated in Fig. 5. Intense crushing and production of open fissures parallel or nearly parallel to the short diagonal of the fracture cleavage blocks is certain to result from continued application of the same stress that produced the fracture cleavage. Chrysotile veins fill these complex secondary crush fractures.

Hydrothermal Alteration Along the Veins.—Hydrothermal alteration is almost absent along veins in the Lowell deposit but is distinct in the Gallagher bodies. Measurements of the width of altered zones along chrysotile veins in both quarries at this mine are listed in Tables II and III. The tables show that the

TABLE II.

RELATIVE WIDTH OF ALTERATION ZONE AND VEIN.—WESTERN QUARRY.

Serp. Zone	Vein	Serp. Zone	Serp. Zone	Vein	Serp. Zone
0.74″	0.56″	0.72″	0.74″	0.42″	1.00″
1.00	0.42	0.90	0.66	0.50	0.62
0.68	0.38	0.70	0.32	0.36	0.38
0.00	0.50	0.84	0.10	0.12	0.08
0.46	0.24	0.46	0.46	0.22	0.50
0.48	0.18	0.40			

width of altered zones along veins bears no relation to vein width and commonly varies on the walls of the same vein. The unaltered rock is dull grayish green whereas the altered zone is dark

TABLE III.

RELATIVE WIDTH OF ALTERATION ZONE AND VEIN.—EASTERN QUARRY.

Serp. Zone	Vein	Serp. Zone	Serp. Zone	Vein	Serp. Zone
0.38″	0.16″	0.40″	1.60″	0.70″	2.70″
0.80	0.50	0.72	0.38	0.20	0.40
0.74	0.02	0.40	0.40	0.16	0.40
0.00	0.14	0.04	0.14	0.16	0.24
0.60	0.50	0.60	0.24	0.08	0.30
0.00	0.08	0.00	0.28	0.22	0.26
0.70	0.44	0.48	0.00	0.22	0.00
0.10	0.12	0.22	0.70	0.40	1.00
0.36	0.14	0.20	0.80	0.06	1.10

green. Two factors affect the width of the altered zone. Close spacing of veins seems to increase the extent of serpentinization, possibly due to increase of porosity by secondary fractures of microscopic size. Depth of penetration of serpentinizing solutions is controlled also by porosity or spacing of the olivine grains in the peridotite. Peridotites with strong primary flow structure as at the Gallagher Mine are much more porous than those that lack this structure, as for example, the Lowell mass.

ORIGIN OF THE VEINS.

The origin of the chrysotile filling the crush fractures has been explained in a number of ways. The most common explanations are:

1. Recrystallization of the serpentine walls.
2. Growth of capillary crystals and force of the growing crystals pushing apart the walls of the fissures.

Many features of the major structures of the vein systems and structures of the veins themselves present strong objections to these views. They fit much better the picture of fracture filling as presented by Ries.[7] Each of the earlier possibilities are considered.

Recrystallization.—Serpentine inclusions in the chrysotile veins are recrystallized but crystals so formed are perpendicular to the

[7] Ries, H.: Bull. Geol. Soc. Amer., vol. 41, p. 237, 1930.

walls of the inclusion and rarely parallel to the chrysotile fibers (Fig. 6). Relatively straight borders to the inclusion indicate slight if any replacement by the asbestos. This indicates that the adjacent chrysotile was not recrystallized from the inclusions.

Compound veins and cross veins (Fig. 7) found in many places argue against a recrystallization origin because the only material to be recrystallized or replaced is asbestos. Fibers adjacent to these cross veins show no replacement and the borders have the complementary walls of filled fractures.

Some veins are composed of sheaf-like bundles of serpentine fibers extending outward for varying distances from a central fissure filled by magnetite and matted serpentine. Remnants of olivine with sheafs of serpentine sticking into it commonly extend to the magnetite-serpentine center. As a rule these veins are narrow and irregular with walls penetrated by recrystallized sheafs that terminate according to the structure of the rock (Fig. 10). This type of vein with its sheaf-like aggregates of recrystallized serpentine is very distinct from the chrysotile type with parallel fibers and complementary walls (Fig. 11).

Chrysotile contains less iron oxide than the walls of the veins. Magnetite found in the veins has been regarded as iron oxide left over by recrystallization of the massive serpentine to chrysotile. Some chrysotile veins have fibrous magnetite replacing the chrysotile and extending across dragged fibers. The magnetite becomes fibrous wherever a magnetite vein cuts into the asbestos; where chrysotile has been dragged oblique to the walls, magnetite fibers are more nearly perpendicular to the walls than those of chrysotile. Many magnetite fibers have been bent or broken at one end so that they almost parallel the direction of the chrysotile fibers; in other cases, the broken or bent parts cut across the chrysotile direction; but in every instance the deflection of the magnetite fibers is in the direction of drag of the veins and is less than the drag on the chrysotile. This seems to indicate that the magnetite was crystallized after the drag on the chrysotile began and therefore is a later introduced mineral rather than a simple recrystallized product of the chrysotile stage.

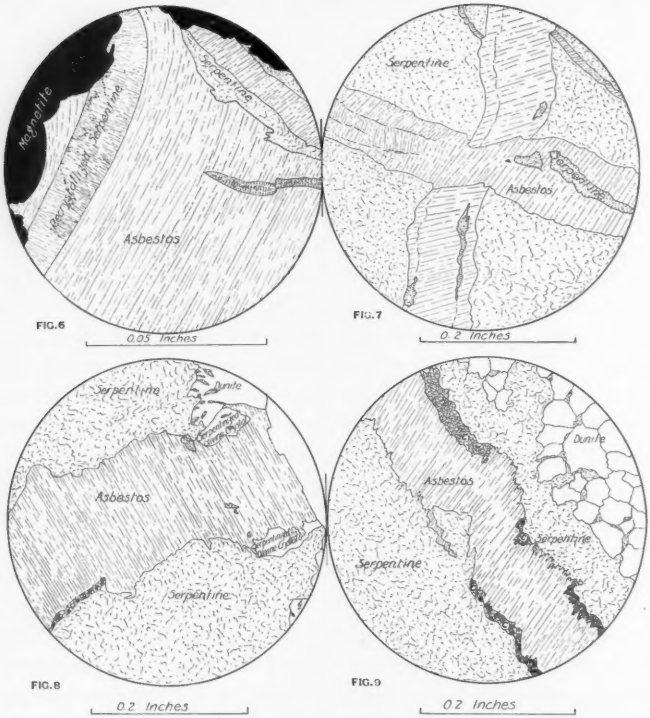

FIG. 6. Camera lucida drawing showing recrystallized serpentine of inclusions in vein from the Gallagher pit. Recrystallized fibrous serpentine is in sheaf-like aggregates approximately perpendicular to the walls of the inclusion. Vein asbestos is in parallel fibers crossing from wall to wall of the vein and not necessarily perpendicular to the vein walls.

FIG. 7. Camera lucida drawing of intersecting compound veins from Moretown, Vt. The walls show complementary form where inclusions are absent. Observe especially offset of the oldest (narrow) vein at top; offsetting is not directly along the length of the fibers. Compound structure of some veins is illustrated by the youngest (horizontal) vein shown at extreme left.

FIG. 8. Camera lucida drawing showing asbestos vein splitting a serpentinized olivine crystal. Observe how closely the two parts of the olivine crystal fit into one another.

FIG. 9. Legend on next page.

Force of Growing Crystals.—The torsion crack form of most veins indicates that the openings were produced by the same stresses that produced the fracture cleavage. Growing crystals may exert on the walls of the openings in which they grow, pressure equal to their crushing strength. However, this pressure does not begin to approach the pressure that produced the fracture cleavage and was exerted against the blocks; these crushing pressures would counteract any exerted by growing crystals against free blocks. Pressures arising from crystals growing in cracks closed at the ends would not open them because the tensile strength of the blocks approximates the crushing strength of the crystals and the lateral pressure producing the fracture cleavage more than offsets any difference.

Filled Fissures—Introduced Material.—The major vein form suggests fissuring by torsion forces arising from shift of fracture cleavage blocks on one another. Irregularities in one wall of a vein fit into those in the other. Specimens were collected for microscopic examination to determine whether the walls were really as complementary as they seemed. If the irregularities and structures on one wall could be matched perfectly into those on the other, then a fracture-filling origin would be a more tenable hypothesis than a recrystallization or replacement one. Also if the openings were produced by the force of growing crystals, irregularities and structures on opposing walls would be offset along the length of the chrysotile fibers.

Large specimens were mounted in an adjustable holder and cut so that the chrysotile fibers lay in the plane of the cut. Many veins showed structures offset along the length of fibers but an equally large number showed complementary structures as far from this position as the vein was wide. This petrographic evidence checks up major field evidence to indicate that

FIG. 9. Camera lucida drawing of asbestos vein with carbonate walls. The complementary form of the walls is partially destroyed by penetrating points of asbestos fibers but is evident in the major outline. The penetrating points of fibers indicate replacement of serpentinized and carbonated (*C*) walls. This type of enlargement takes place chiefly along carbonated sections of veins.

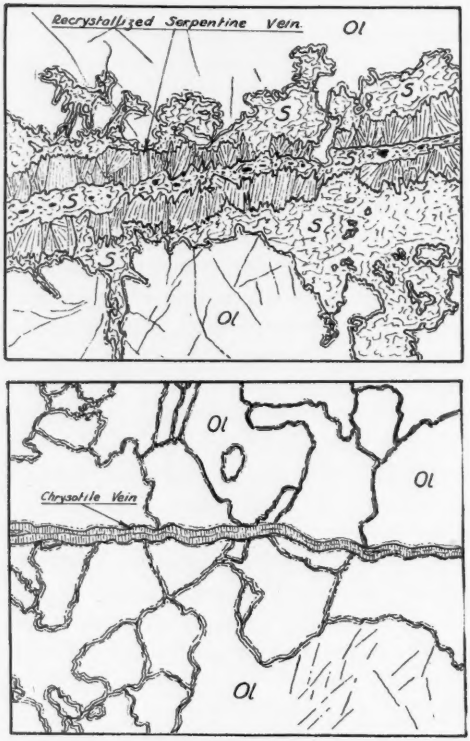

FIG. 10 (above). Camera lucida drawing of asbestos vein formed by recrystallization of dunite from Lowell. × 40. The vein shows a central serpentine-magnetite parting. Sheaf-like bunches of recrystallized serpentine (low relief) extend into the olivine (*ol*) and serpentine (*s*).

FIG. 11 (below). Camera lucida drawing of narrow asbestos vein in dunite from Lowell, Vt., to show structure. Approximately × 40. Walls of the vein through the center of the drawing are sharply defined and complementary; asbestos fibers are arranged in parallel. *Ol*, Olivine.

even although growing crystals may make openings, growing crystals did not make openings for these chrysotile veins.

Evidence of Fracture Filling.—Complementary walls and matched structures in the veins suggest filled fissures. However, it is the type and detail of the matched structures that is most convincing. A narrow asbestos vein at Moretown, Vt., is intersected by a wider one oblique to the direction of the first (Fig. 7). The later fissure broke along the asbestos cleavage making a sharp angle in the wall; beyond the small vein the fissure resumes its average direction. This same structure is repeated where a third asbestos vein cuts the second; the break follows the asbestos cleavage and the wall irregularities match perfectly. In the instance of the earliest intersection the offset walls do not meet at the ends of the fibers, and in the second instance they do.

A vein from the Gallagher mine shows a complementary form of opposing walls in equal detail. A large serpentinized olivine crystal is slit by a sickle-shaped fissure and filled by chrysotile (Fig. 8). The straight handle and curved blade of the sickle may be recognized on both sides of the vein in this singular, large crystal; however the fine tip of the blade of the lower part is broken off and is probably represented by one of the inclusions.

Many veins have a split carbonate vein for walls. The width of the carbonate zone is constant through long stretches. In places carbonate shows on only one side, or it may be split to appear in diminished thickness on both sides. It gives all indications of having been a vein zone that has been reopened for chrysotile filling.

Complementary structures are difficult to identify in veins with many inclusions. Inclusions represent fragments from the walls, usually the projecting points. Consequently, when a point breaks off and leaves an indentation, the place corresponding to the indentation on the opposing wall is not a projection but a hole. Inclusions proved extremely confusing before their significance was understood; in places they are offset so that their point of origin can be identified and in other places they have been turned around and moved so far from their source that they cannot be

fitted into any visible part of the walls. Movement of inclusions in this fashion would be impossible except in open spaces, or spaces filled by solution; their position would be limited close to the source if the walls were pushed apart by crystals as they grew.

Evidence of Replacement.—Fibers penetrate slightly the walls, especially carbonated walls, of the wider veins and indicate irregular replacement (Fig. 9). However, even in these instances major forms on the opposite sides can be matched. This seems to indicate that, although replacement masks the simple fracture-filling type of vein, it is not of major importance in making the deposits or in increasing the length of fiber by an appreciable amount.

SUMMARY OF MAJOR FACTORS OF VEIN MAKING.

Serpentine areas lie between the rising Green Mountain geanticline and dominantly sinking Memphremagog trough. Fracture cleavage and shear cleavage are predominating structures along borders of serpentines. Further adjustment of the rock mass has produced torsion cracks and crush fractures in which the asbestos is found.

Hydrothermal alteration appears along veins in places but seems to have no effect upon the veins themselves. Recrystallization and replacement lack prominent positions in making the chrysotile veins; neither are important enough to change even the general fracture form; both are in evidence but only in minor and relatively unimportant rôles.

Fracture filling greatly outweighs replacement or recrystallization as the origin of the chrysotile veins. Detailed study of the serpentines and peridotites, the veins, and the mineral relations in them gives a picture of asbestos as a filling material in torsion cracks and crush fractures.

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ADDITIONAL NOTES ON SECONDARY CONCENTRATION OF LAKE SUPERIOR IRON ORES.

JOHN W. GRUNER.

INTRODUCTION.

SINCE the beginning of the study of geology there have arisen from time to time controversies as to the origin of certain classes of mineral deposits. In such cases the deposits were usually of a type which admitted of an ambiguous interpretation because the minerals in them are now known to form by quite different geological processes. One needs to mention only the kaolin deposits. Many of them are certainly of pneumatolytic and hydrothermal origin, others are surely due to weathering. The present discussion [1] as to the origin of the Lake Superior ores is of this kind.

It has been taken for granted by the majority of the geologists that the word oxidation was almost a synonym for weathering. Of course everyone knows that hematite deposits may be of contact or hydrothermal origin, if associated with intrusive rocks, though the reason for the ferric state of iron is little understood. By experimental evidence it has now been shown that hot water will decompose in the presence of certain ferrous minerals, and ferric iron and hydrogen will result. It would be strange if such a simple chemical process were not commonly active in nature in places where the hydrogen could escape easily, in other words relatively near the surface. A confirmation of this view seems to have been discovered very recently by Fenner and Day [2] during drilling in Yellowstone Park, where specular hematite forms in

[1] Gruner, J. W.: "Hydrothermal Oxidation and Leaching Experiments; their Bearing on the Origin of Lake Superior Hematite-Limonite Ores." ECON. GEOL., vol. 25, pp. 697–719, 837–867, 1930. Leith, C. K.: Secondary Concentration of Lake Superior Iron Ores. ECON. GEOL., vol. 26, pp. 274–288, 1931.

[2] Ann. Rept. of the Director, Geophys. Lab., Yearbook No. 29, p. 77, Washington, 1930.

the hot alkaline waters notwithstanding the presence of hydrogen sulphide. Such oxidation might be difficult to distinguish from oxidation due to weathering. If specular hematite and martite [3] were found in a deposit, most geologists would probably think of higher temperatures than those of weathering, especially if the country rock were propylitized and sericitized. Such conditions are found in some of the Lake Superior iron ores.

LEACHING OF SILICA.

The evidence of hydrothermal activity in the Lake Superior region seems to be somewhat confused and weakened due to the fact that leaching of silica [4] has taken place on a grand scale. This is a process usually associated in the minds of geologists with certain types of weathering of silicate rocks (lateritization). Important in connection with the leaching of quartz from the iron formation in the Lake Superior region is the observation that quartz seems to be almost unattacked in the process of lateritization, according to Harrassowitz.[5]

Dr. Leith [6] thinks that the weathering hypothesis may "need expansion and qualification" to explain the ever increasing depth at which ore bodies are found, having in mind ore bodies around

[3] My work on the oxidation of magnetite is criticized by Leith (*op. cit.*, p. 282). He states: "Detailed studies of martite have shown it to be formed both by slow oxidation at ordinary temperatures and under thermal conditions," giving as his authority Lillian H. Twenhofel (ECON. GEOL., vol. 22, pp. 180–188, 1927). But Miss Twenhofel, whose paper I discussed three years ago, mentions only temperatures of 220° C. and above, and oxygen gas as an oxidizing agent.

[4] With regard to my experiments on the solubility of SiO_2 at higher temperatures, Leith states (*op. cit.*, p. 275): "Gruner seems to have overlooked the work of Lenher and his associates who, prior to 1921, presented experimental evidence of the efficacy of hot solutions in leaching silica. In fact the increased solubility of silica at higher temperatures was known long before this." This statement would imply that experiments on solubility are useless because we have known for generations that solubility of almost all substances increases with rising temperature. I was quite familiar with the experiments of Lenher, who did not go above 90° C. and used freshly prepared gelatinized SiO_2 and an impure chert. I referred to them indirectly when I wrote (*op. cit.*, p. 700) that temperatures up to 90° C. were relatively inefficient.

[5] "Laterit," p. 350, Gebrüder Borntraeger, Berlin, 1926.

[6] *Op. cit.*, p. 283.

3,000 feet or deeper. Depth is a relative term but most geologists would agree that leached iron ore bodies due to weathering are exceptional even when they reach 500 to 1,000 feet. There seems to be no leaching of silica known to such a depth except in ores of the Lake Superior type. In the Birmingham, Alabama, district calcium carbonate has been leached from the iron ores to a maximum depth of about 400 feet along the dip, but Burchard [7] states expressly that the ratio of Fe to Al_2O_3 to SiO_2 is not affected at all by the leaching. The same observation has been made for the oxidized ores of the sedimentary iron formations of Great Britain.[8] There seems to be no record, in the literature of sedimentary iron ores outside the Lake Superior ores, to the effect that leaching has removed essential amounts of silica, if any at all, at and near their oxidized outcrops.

One of the greatest obstacles for the acceptance of the weathering hypothesis is the fact that most of the silica that was leached was in the form of quartz and not in the state of an indefinite, more or less hydrous form of silica or silicate. In the productive part of the Mesabi range the so-called taconite or ferruginous chert is a fine-grained quartz-magnetite-ferrous silicate (amphiboles, etc.) rock. This taconite, when 2,000 feet under Virginia slate, is not essentially different from that near the surface. The ores were formed *directly* from this highly resistant rock. The taconite layers, consisting almost entirely of magnetite and quartz (" cherty divisions "), yielded just as readily to the solution as the so-called greenalite layers. On the Gogebic range, according to Aldrich,[9] the ores were formed from the beds high in quartz in preference to the slaty siderite members of the iron formation. Even small portions of the basal Palms quartzite are dissolved entirely. The Vermilion ores were formed directly from a highly metamorphosed quartz-magnetite-hematite-amphibole rock, as

[7] Burchard, E. F., and Butts, C.: " Iron Ores Fuels and Fluxes of the Birmingham District, Alabama." U. S. Geol. Survey Bull. 400, pp. 27 and 36, 1910.

[8] " Iron Ore Resources of the World," XI. Internat. Geol. Congress, vol. II., p. 634, 1910. " Iron Ore," Imperial Mineral Resources Bureau, Part I., pp. 49 and 69, 1922.

[9] Aldrich, H. R.: " The Geology of the Gogebic Iron Range of Wisconsin." Wis. Geol. and Nat. Hist. Survey Bull. 71, p. 140, 1929.

proved by the highly folded and banded portions of jaspylite included in the porous ores. The same is true of large portions of the hard ore of the Marquette range. The soft Marquette ores seem to have formed from sideritic "chert" directly, yielding a very fine-grained hematite with some specular crystals large enough to be visible to the naked eye.

The question to be approached then is: Can natural hydrothermal solutions remove silica without substituting something else? There is abundant evidence that very large bodies of siliceous rocks have been *replaced* by carbonates.[10] We also find many examples of replacement of siliceous rocks by iron oxides among the iron ores. For instance, the large metasomatic Kromdraai deposits of hematite have replaced very large amounts of felsite agglomerate and sometimes quartzite,[11] in the roof of the Bushveld Complex. No igneous intrusions are in the immediate vicinity of these ores. Since the iron salts in these solutions (at Kromdraai) probably were not the cause of the solution of the silica, some other reagent must have been in them, unless the hot water itself was a sufficient solvent. If these solutions had entered an iron formation the silica would have been removed and secondary hematite would have been deposited. Deposits of this kind are described by Burchard[12] and by Lovering.[13]. They resemble closely most of the hard ores of the Marquette and

[10] Ransome, F. L., and Calkins, F. C.: The Geology and Ore Deposits of the Coeur d'Alene District, Idaho." U. S. Geol. Survey Prof. Paper 62, p. 138, 1908. Cooke, H. C.: "Kenogomi, Round and Larder Lake Areas, Timiskaming District, Ontario." Can. Geol. Survey Mem. 131, p. 48, 1922. Brögger, W. C.: "Die Eruptivgesteine des Kristianiagebiets," vol. 4, pp. 270–273, 1921. Butler, B. S.: "A Suggested Explanation of the High Ferric Oxide Content of Limestone Contact Zones." Econ. Geol., vol. 18, p. 401, 1923. Knopf, Adolph: The Mother Lode System of California. U. S. Geol. Survey Prof. Paper 157, p. 45, 1929. Also Gruner, J. W.: Econ. Geol., vol. 21, p. 634, 1926. Collins, W. H., Quirke, T. T., and Thomson, Ellis: Michipicoten Iron Ranges. Can. Geol. Survey Mem. 147, p. 31, 1926.

[11] Wagner, P. A.: "The Iron Deposits of the Union of South Africa." Union of South Africa Geol. Survey Mem. 26, p. 44, 1928.

[12] Burchard, E. F.: "The Pao Deposits of Iron Ore in the State of Bolivar, Venezuela." Am. Inst. Min. and Met. Eng. Tech. Pub. No. 296, p. 18, 1930.

[13] Lovering, T. S.: "The Rawlins, Shirley and Seminoe Iron Ore Deposits, Carbon County, Wyoming." U. S. Geol. Survey Bull. 811, p. 233, 1930.

Vermilion ranges. If no iron salts had been in the hot solutions that produced this type of replacement, there probably would have been only leaching of silica. Hot solutions high in carbonates could leach silica. Whether they deposited carbonates in place of silica or not would depend largely on the concentration and supply of CO_2. We might conclude then that because leaching has generally not been recognized heretofore (except in minor occurrences) as a hydrothermal process, is no reason that it could not be of great importance. Hydrothermal leaching also would have a tendency to alter or destroy any silicates ordinarily associated with contact phenomena or high temperatures.

HYDROTHERMAL ROCK ALTERATION AND OXIDATION.

The opinion has been expressed[14] that hydrothermal and contact effects on both basic and acid intrusives in the majority of cases result in increases of silica relative to aluminum and iron and increases of ferrous over ferric iron. A study of plates V, VI, XI and XV in "Metamorphic Geology"[15] shows that silica on an average remains constant or decreases slightly with respect to alumina. Ferrous iron with respect to ferric decreases just as commonly as it increases, and the total iron often decreases markedly (except in acid rocks, Plate XV.) resulting in bleaching, so common in this connection. Great losses of silica and gains of potash are also conspicuous in shear zones in some quartzites that are ascribed to dynamic metamorphism.[16]

The analysis of a so-called "weathered" diabase dike of the Gogebic range[17] is instructive on account of a tenfold increase of potash and a large decrease in iron and silica. Increases of

[14] Leith, C. K.: *op. cit.*, pp. 281–282.

[15] Leith and Mead. New York, 1915.

[16] Leith and Mead (*op. cit.*, Plate XI.) discuss in detail three analyses, two of them from the Marquette range, in which shear zones cross the bedding. The quartzite is altered to sericite schist. It is also interesting that "dynamic metamorphism" of basic igneous rocks (Plate XIII.) in the Menominee and Marquette districts produces a conspicuous loss of silica and great gain of CO_2 in all analyses but one, in which they remain constant. These analyses are from rocks 1½ to 2½ miles distant from iron mines.

[17] Leith and Mead, *op. cit.*, Plate IV. Also see Van Hise, C. R., and Leith, C. K.: U. S. Geol. Survey, Monograph 52, p. 246.

potash in altered diabase dikes of the Lake Superior region are common and the total potash reaches 8 per cent in some dikes in the Marquette district, according to Dr. C. J. Muller.[18]

The formation of hematite or the oxidation of ferrous iron to hematite with accompanying thorough alteration of igneous intrusives is not confined to the Lake Superior region, but is known all over the world. Propylitization, sericitization and kaolinization in such occurrences grade into one another, sometimes one, sometimes the other process predominating. Tegengren's [19] monographs on the iron ores of China contain many references to these alterations. In summarizing he states (Part I., p. 101): "There seems to be a territorial connection between the distribution of the rich ore concentrations and the occurrence of highly altered and often kaolinized dikes and apophyses from the granitic intrusives . . . and this assumption is strengthed by the close resemblance of these ores in structure and habits with the contact-metamorphic ores of the Yangtze valley." He favors (p. 100) a deep-seated igneous source for the solutions which leached the silica from the Archean ores. Wang [20] describes the Tayeh iron ores and comments on the thorough decomposition of the intrusives due to the action of hot waters. He also mentions the essentially complete absence of contact minerals.

Bogdanowitch,[21] in describing the hydrothermal and contact ores at Gora Magnitnaja and Bogoslowskij mentions the great kaolinization and martitization even at the bottom of the ore bodies. Kemp [22] in discussing propylitization and kaolinization at Daiquiri states: "So constant is the change near the ore bodies that one can not avoid the conviction that thermal waters have been actively circulating." Foshag [23] describes extensive hydro-

[18] Geologist of the Oliver Iron Mining Co. Personal communication.

[19] The iron ores and iron industry of China. Mem. Geol. Survey of China, series A, No. 2, part I., 1921; part II., 1924.

[20] Wang, Chung Yu: "The Tayeh Iron Ore Deposits." Trans. Am. Inst. Min. Eng., vol. 58, p. 446, 1918.

[21] Bogdanowitch, K.: "The Iron Ore Resources of the World." XI. Internat. Cong., 1901, pp. 395 and 401.

[22] Kemp, J. F.: "The Geology of the Iron Ore Deposits in and Near Daiquiri, Cuba." Trans. Am. Inst. Min. Eng., vol. 53, p. 17, 1916.

[23] Foshag, W. F.: "Mineralogy and Geology of Cerro Mercado Durango, Mexico." Proc. U. S. National Museum, vol. 74, p. 7, 1928.

thermal martitization and kaolinization with introduction of some diopside at Iron Mountain, Durango. Associations of martite and goethite like those at Durango occur also in the Marquette and Gogebic districts. Bloch,[24] in a detailed description of the iron ores near Stollberg, states that the diabase dike (parallel to and in the ore) is highly decomposed from its nearly black color to a nearly pure white kaolin-like mass. The country rock is similarly decomposed. Decomposition is greater in the lower than in the higher levels. Although no sulphides occur in the hematite-limonite ores, they have not been removed at all in the highly decomposed rocks adjoining the ores. This is one of the arguments against descending waters, according to Bloch.

One of the most puzzling occurrences has been the peculiar oxidation of siderite to "Rotspat" and specular hematite in connection with diabase intrusions in the famous Siegerland siderite veins. This oxidation is independent of limonitization from the surface. Two kinds of diabase intrusions are found in the veins. One kind produces magnetite from siderite by contact action, the other causes oxidation to hematite; and thorough decomposition and bleaching of the intrusive and of the country rock is then connected with it. Bornhardt[25] explained this alteration formerly by infiltration of cold sodium chloride water but said that this was not at all a satisfactory explanation. Recently Schneiderhöhn[26] investigated this oxidation and ascribed it to thermal or hydrothermal effects, a conclusion which the present writer had also reached. Many other examples of such alteration may be found in literature. Some of them are ascribed to cold waters.

According to Leith,[27] serpentine, talc, chlorite and specular hematite in and at contacts with ore may be explained either by "weathering conditions or dynamic metamorphism." Although

[24] Bloch, A.: "Die Erzlagerstätte bei Stollberg in Mittelschweden." Zeitsch. f. prakt. Geol., p. 103, 1923.

[25] Bornhardt, W.: "Ueber die Gangverhältnisse des Siegerlandes und seiner Umgebung." Zeitsch. f. prakt. Geol., p. 399, 1913.

[26] Schneiderhöhn, H.: "Vorläufige Mitteilung über pyrometamorphe Paragenesen in den Siegerländer Spateisensteingängen." Zeitsch. f. Kristallog., vol. 58, p. 325, 1923.

[27] *Op. cit.*, p. 282.

it can not be proved at present that these minerals can not originate by weathering, the majority of geologists will agree that they are probably more commonly the products of hot waters and metamorphism. Their occurrence in veins and cavities in the soft iron ores can not be linked with metamorphism since these minerals are later than this process. Why the talc schist at the contacts of the ores on the Menominee range is thought to be of hydrothermal origin has been stated before.[28]

The last paragraphs on rock alteration and oxidation have shown that these processes in the Lake Superior iron ores may very well be due to hydrothermal solutions, especially on account of the occurrence of specular hematite, martite, talc, chlorite, sericite and serpentine. Small amounts of chalcopyrite also, which have been reported from all ores except those of the Cuyuna range, could hardly be due to oxidizing cold solutions.

POSSIBLE RELATION OF ORES TO ANCIENT EROSION SURFACES.

An attempt has been made to correlate the deep ores with a number or succession of ancient erosion surfaces[29] at or near which these ores might have been formed. Concentration of ores at ancient erosion surfaces would imply later burial and at least tilting if not folding of the formations including the ore. It is difficult to see how soft ores could have been subjected to such movements without consolidation and cementation. Besides, in most cases there is no indication whatsoever that an ancient erosion surface was closer to the soft ores than the present surface. Practically always, slates were deposited on the iron formations conformably. These slates were not removed by erosion except in the case described below. Moreover, the ores are usually closer to the bottom than to the top horizons of an iron formation. The positions of most of the ore bodies and their relations to dikes show clearly that the soft ores formed in practically their present attitudes. In the class of soft ores, however, are included all ores of the Gogebic, Mesabi, Menominee, Cuyuna, Crystal Falls, Iron River, and 70 to 80 per cent of the Marquette ores. The ores

[28] Gruner, J. W.: *op. cit.*, p. 846.
[29] Leith, C. K.: *op. cit.*, p. 283.

of the Ely trough of the Vermilion range also belong here because they are very porous, though the individual grains are specularite.

In the Sunday Lake district of the eastern Gogebic range a large overthurst fault developed before the iron formation was tilted to its present position. Erosion removed the overlying Tyler slate in this area and certain ore bodies (Chicago, Pike, and Brotherton mines) formed due to weathering near this old erosion surface, according to Lake.[30] Fig. 1 is a cross-section of one of these ore bodies. If these ore bodies are due to circulating cold waters it is strange that none of them formed right on the erosion

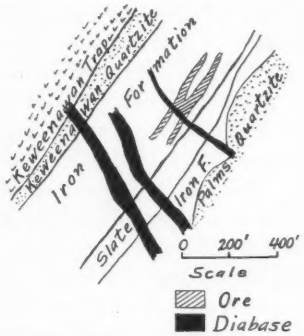

FIG. 1. Brotherton ore body on East Gogebic range. After M. C. Lake. Keweenawan quartzite overlies the iron formation uncomformably.

surface. The closest is over 100 feet below the ancient surface and most of them are much farther away. Intrusive and extrusive activity was on a large scale in this area and at least two periods of it are distinguishable. That most of the major soft-ore bodies should be connected "usually through ore extensions and occasionally through more or less obvious channels of circulation" with the present surface is to be expected regardless of whether the leaching solutions were hot or cold. There probably exist no hydrothermal deposits of any kind in which such connections could not be found. The problem, then, of possible older

[30] Lake, M. C.: "Geology of Wakefield Area of the Eastern Gogebic Range," in The Iron Ores of Lake Superior, by Cromwell and Murray, Cleveland, 1917.

erosion surfaces and weathering of iron formation narrows down to the relatively few hard ore bodies, in particular to the "Republic Trough" mentioned by Leith.

The Ely Deposit.—It might be well to summarize briefly the facts pertaining to one single deposit of the region with the weathering and hydrothermal hypotheses of concentration in view. The "Ely Trough" is probably most suitable for this purpose because cross-sections of its ore bodies and other detailed descriptions are readily available in the literature. The most complete account is by Abbott.[31] The present writer [32] has also described certain features of these deposits and discussed their origin.

The Ely Trough is a synclinal structure of iron formation in greenstone and porphyries, and probably in some slates on its north limb. It is about 8,000 feet long from east to west. Its maximum width is about 1,500 feet. It has so far produced 50 million tons of ore. The "bottom" of the structure pitches eastward at an angle of about 45° for the first 1,500 feet and then flattens to a low angle. The sides of the syncline are steeply inclined toward its axis. The iron formation in the structure is highly metamorphosed and brecciated. Large basic intrusives and a few small acid ones invade the iron formation and ore in an intricate manner. Practically all of those intrusions were mistaken as older than the iron formation in the early days and were called greenstone and paint rock. They are highly altered to chlorite, sericite,[33] and kaolin where in contact with ore.

The ores are specular hematite with minor amounts of martite. They are quite porous, though in places, especially at the east end, cemented by secondary siderite and calcite. Much secondary specular hematite has been introduced. The ore bodies are large though not necessarily connected. They are at or near the bottom and sides of the structure and finger out into the overlying jaspy-

[31] Abbott, C. E.: The Iron Ore Deposits of the Ely Trough, Vermilion Range, Minnesota. Proc. Lake Superior Min. Inst., vol. 12, pp. 116–142, 1907.

[32] Gruner, J. W.: "The Soudan Formation and a New Suggestion as to the Origin of the Vermilion Iron Ores." ECON. GEOL., vol. 21, pp. 629–644, 1926.

[33] The analysis of a highly altered and bleached diabase dike from the 12th level of the Pioneer mine showed 6.43 per cent. K_2O and .06 per cent. Na_2O. Analyst, Tohru Kameda, Rock Analysis Laboratory, Univ. of Minn.

lite.[34] They are covered by 200 to 1,000 or more feet of unleached iron formation except at the extreme west end, where ore outcropped in two small areas. Ore reaches to a depth of at least 1,500 feet. Many beautiful large quartz crystals, some pyrite and occasional chalcopyrite are found in cavities in the ore.

All investigators now agree that the concentration of the ores was later than the last metamorphism and later than the intrusion of the youngest dikes. Leith[35] thinks that the surface waters which leached the ores entered the structure at the extreme west end where the two small outcrops of ore were situated. Unless the area of these outcrops was sufficiently large for collecting the leaching waters, it must be assumed that the former intake area has been eroded. At a pitching angle of 45° an intake of a size sufficient to gather much water would have had to be a great vertical distance above the present peneplain. All the descending water would have had to pass through a relatively small cross-section at the level of the present surface. A little farther down, however, the vertical cross-section of the ore body increases enormously. The lower limit of the ore bodies is determined by the walls of the "trough" and the intrusives, and is very irregular. The upper limit is even more so, for some ore bodies may be a thousand feet in vertical extent.

There are only two methods by which cold water can circulate vigorously under such conditions. In the first one a low outlet may be assumed near the bottom of the synclinal structure. Water would move by gravity on an impervious stratum toward this outlet. If this impervious layer contained basin-like depressions lower than the outlet the water should become nearly stagnant in them. After the most direct channel for the flow was once established by leaching, the water should follow this channel for indefinite periods of time. The water could not rise to a great height above the bottom of the established channel. No one has ever proposed an outlet *near the bottom* of the Ely Trough, for the whole geological setting of the region makes such a low outlet practically impossible. The other method of

[34] See sections by Abbott, and in Mon. 52, p. 138.

[35] *Op. cit.*, p. 277.

circulation of ground water is artesian. An impervious cover on the jaspers of the trough and an outlet somewhere near the present surface would be required. As pointed out before [36] this type of circulation should have moved through the highly fractured jasper directly under the impervious cover, and the portions of the trough where the ore bodies are actually found should have been filled by stagnant water.

If hydrothermal conditions existed it is easy to account for the positions of the ore bodies because they are largest where the intrusives are biggest and most numerous. The hot solutions leached at depth and after they became saturated with silica on their way up, they passed through the iron formation still oxidizing but not able to do any more leaching. It seems to the writer that the solution of silica at great depth in the Ely Trough by descending waters cannot be considered unless this water was heated by the intrusives, which is of course a possibility.

ADDITIONAL NOTES ON INDIVIDUAL DISTRICTS.

A few more facts must be mentioned, which are arranged best in the order of districts in which they occur. Though the following points may seem disconnected they are essential for an understanding of the problem.

Marquette Range.—The soft ores in the Negaunee area are rarely if ever found directly on the Siamo slate. Some unleached iron formation usually occurs between the slate and the ore. On the other hand, much of the richest ore is found in direct contact with the dikes. The ore is commonly more closely associated with intrusives than it is with the folded Siamo slate footwall.

The martitization of some of the ores at the contacts with the dikes is especially interesting. The martite octahedra vary in size from microscopic to 3 mm. and bigger. A diameter of ½ mm. is near the average in certain places. The number of octrahedra decreases gradually from ore consisting almost entirely of martite to altered rock without any magnetite or martite. Commonly it is difficult to see the exact contact between iron formation

[36] ECON. GEOL., vol. 21, p. 639, 1926.

and dike. The alteration of the dikes consists of chloritization, sericitization, kaolinization and the formation of talc-like material. Usually there is bleaching of the intrusive with slight reddening in some layers. Martitization has penetrated in the dikes as far as the secondary magnetite reached, which is often several inches and sometimes much more. The iron for the magnetite was either introduced by solutions and gases or was extracted by them from the basic dike material. Since alteration makes the dike material impervious to cold solutions, and this process clearly preceded the formation of the magnetite crystals, it does not seem reasonable that cold water could have caused martitization. It may also be significant that good specularite as joint fillings is occasionally found in the so-called lean hard ores which are partially leached and are semiporous.

Menominee Range.—Leith [37] makes this statement in his recent paper: "No igneous intrusions or extrusions are known in the Menominee district." But in Monograph 52 [38] is stated: "A few small dikes cutting the schists (Quinnesec) are normal diabases and basalts, identical in composition with some of the rocks cutting through the iron-bearing beds." Intrusives also cut the overlying Michigamme slate along the whole length of the range.

Gogebic Range.—The writer examined Gogebic ores in polished sections. The ore consists mostly of specular hematite with crystals up to 1 mm. in diameter. Large portions of ore, however, are so fine-grained and porous that they cannot be examined in polished sections. Occasional crystals of pyrite and even chalcopyrite are found. Much secondary quartz, as beautiful little crystals, lines cavities in the ore. In places secondary hematite has been introduced yielding exceedingly dense, hard, blue ore.

The very high concentration of chlorine (probably as $CaCl_2$) in only the deep mine waters, according to Hotchkiss,[39] is of interest since it recalls similar concentrations in the hydrothermal copper ores of Michigan 50 to 100 miles farther east.

[37] *Op. cit.*, p. 280.

[38] Van Hise and Leith: *op. cit.*, p. 344; also Plate XXVI.

[39] Hotchkiss, W. O.: "Recent Developments in the Geology of the Gogebic Range." Proc. Lake Superior Mining Inst., vol. 23, p. 51, 1923.

It has been stated that the dikes on the Gogebic range were nearly vertical at the time they were injected into the iron formation, and ore concentration occurred during and after tilting. Intrusive activity lasted over a long period or perhaps two periods, the Upper Huronian and the Keweenawan. Some of the dikes are younger than others, as stated on a previous page. Sills are also common. Since the majority of the dikes make an angle of about 80° with the sediments, it is probable that the iron formation dipped at least slightly to the north. It was suggested by the writer,[40] though he was apparently misunderstood, that the hot gases and solutions due to the intrusions that supplied the dikes, not necessarily from the dikes, prepared the way for the main solutions by decomposing the ferrous minerals and creating porosity in the iron formation. The gases and solutions probably escaped largely up the dip even though it may not have been more than 10° in the beginning. Since some of the dikes were the feeders to enormous flows above the Tyler slate, considerable amounts of magma may have passed through them for some time. The main solutions for the leaching probably rose "chiefly through the faults" as stated before. These also produced a number of ore bodies which Aldrich[41] describes as follows: "There are many occurrences of ore in the form of "chimneys" apparently due to the presence of cross fracturing. When these erect bodies coalesce with the more common type of dike-controlled body, the aggregate is a huge concentration. Furthermore, there are innumerable instances of ore bodies developed underneath dikes, apparently due to the complete alteration of the dike rendering it permeable, to the dislocation of the dike by faulting, or to other means of leakage of the oxidizing waters through the dikes. Innumerable dikes are known which carry no ore although oxidation has been intense."

Michipicoten Range.—In the discussion of my paper Leith mentions the Michipicoten range and states that the basic dikes in this region converted siderite to magnetite. The writer did not mention this range previously on account of the peculiar chert-

[40] *Op. cit.*, p. 840.
[41] *Op. cit.*, p. 103.

pyrite-siderite combination in the iron formations. If there was anywhere an opportunity for weathering it should have occurred in the pyrite-siderite formations. But the Helen mine is practically the only ore body in this district. A highly decomposed vertical dike was one of the features in this mined-out deposit. "Down to 280 feet below the surface this dike formed the western termination of the ore, but farther down, in the third, fourth, fifth and sixth levels, a smaller body of ore was found on the west side of the dike." [42] Very large sharply defined pyrite "pockets" and pure white sugary quartz were a peculiar feature in this ore body. This pure pyrite "flowed like sand when an opening was made." If this ore body was produced by weathering something about the process must have differed from ordinary weathering, otherwise the cement between the pyrite in the pockets could not have been removed without oxidation of the sulphide.

Mesabi Range.—Leith [43] writes with respect to dikes which I described as fresh dolerite dikes north of the iron formation: "Pebbles of these dikes exist in the basal conglomerate of the iron-bearing series." The age determination of an intrusive on the strength of pebbles of similar rock in a conglomerate is not without serious objection and has led to errors before, even in this Mesabi area.

Leith also mentions Aurora as the western limit of intrusives in the iron formation. A number of diabase dikes occur, however, 6 to 7 miles west of this town. Ten years ago the writer examined a highly altered vertical dike in the ore of the Belgrade mine. Diabase also intrudes the iron formation below the deepest ore body on the Mesabi range. This ore body is 903 feet deep and lies between Aurora and the Belgrade mine. A small dike was found in the Leonidas mine at Eveleth by the engineers of the Oliver Iron Mining Company in January, 1931.[44] The westernmost intrusive is recorded by Van Hise and Leith [45] themselves as occurring near Keewatin (45 miles west of Aurora),

[42] Collins, W. H., Quirke, T. T., and Thomson, Ellis: "Michipicoten Iron Ranges." Can. Geol. Survey Mem. 147, p. 116, 1926.

[43] *Op. cit.*, p. 281.

[44] Oral communication by Mr. J. E. Wolff.

[45] Mon. 52, p. 178.

where "drilling has penetrated 20 feet of diabase with iron-bearing formation both above and below." It seems that the distribution of these intrusives is such that little doubt can exist any more as to the presence of large masses of them below the iron formation.

It has been stated that no ore bodies exist under the Virginia slate. Positive proof for their absence exists, however, only in places where drilling through the slate and iron formation has been extensive and deep enough. A number of ore bodies exist which are partially under slate. One of them is covered by 150 feet of slate at the place where the ore reaches its greatest depth. There is evidence that erosion has removed at least 125 to 150 feet of taconite in places since the time the ore was concentrated. This is proved by the fact that the top layers of ore bodies were concentrated from taconite, which before slumping must have been at corresponding vertical distances above the present erosion surface. It would be strange, therefore, if the ore bodies which are now close to the Virginia slate had not been covered by it, at least to some extent.

CONCLUSION.

Judging by the great variety of types of iron ore deposits there is every reason to believe that they can be formed under conditions which range from magmatic segregations through contact and replacement deposits to those in which the deposits were concentrated at temperatures close to 100° C. and in which heated ground waters might have had a part. These latter deposits could easily be confused with those produced by weathering. It is even conceivable that weathering could be superimposed upon hydrothermal leaching during and after the last stages of volcanic activity. There seems to be no single criterion for differentiating the effects of weathering from those of hydrothermal oxidation and leaching unless it be the presence of specular hematite and other minerals commonly ascribed to thermal action. Hydrothermal oxidation and leaching should always occur relatively close to the surface or where solutions and gases due to the nature of the formations can ascend rapidly and escape. This latter

condition is not essential in the vein or replacement ore deposits, where solutions must have time for deposition which, therefore, frequently occurs under semi-impervious cappings. As in other mineral deposits which are caused by magmatic activity, not every dike, sill or stock in iron formation can be expected to be associated with ores. It seems, however, highly significant that most if not all of the world's largest oxidized iron ore deposits, whether they were derived from replacement deposits of siderite or from siliceous iron formations, are associated closely with visible intrusions or are in regions where there is evidence of such intrusions over considerable areas. These igneous rocks are usually diabasic or intermediate in composition. Such association can hardly be accidental. Detailed study of the ores of Krivoy-Rog in Russia, Kolhan and Singhblum in India, and the Union of South Africa, of which we have only relatively meager descriptions, will add a great deal to the understanding of processes of oxidation and leaching of iron ores.

In conclusion the writer gratefully acknowledges the stimulating discussions and assistance which he received from many of the mining companies and their staffs. Generous financial help was given by the Oliver Iron Mining Company for experimental research. Mr. E. L. Derby, Jr., Mr. J. F. Wolff, Dr. C. J. Muller; Dr. W. H. Emmons; Dr. F. F. Grout and Dr. G. A. Thiel were of especially great aid to the writer.

UNIVERSITY OF MINNESOTA,
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EDITORIAL

HOW THE KIMBERLITE PIPES SERVE TO REVEAL THE UNKNOWN.

ALL too commonly the geologist is faced with the problem, which may be one of economic importance, of having to decide the presence in depth of one or more older formations, no exposures of which are to be found for considerable distances around because of the blanket of younger strata. By assembling all the data and by reconstructing the paleogeography of the region, he is sometimes enabled to give answer with a certain amount of assurance; in other cases the problem remains doubtful or is insoluble.

An even more difficult question is one of deciding whether a certain formation formerly overlay the area in question, though since removed by erosion, but here again in particular instances deductive reasoning may prove of great value.

It is desired to point out how in southern Africa positive proof concerning the geological character of the concealed depths or even of the now-vanished coverings is, in many instances, furnished by the pipes or dike-like bodies of that remarkable eruptive, ultrabasic material known as *kimberlite*.

Peculiar to those intrusions is the abundance and variety of the contained foreign inclusions, torn off from the walls of the pipes (or fissures) during their mechanical enlargement and buoyed up in the denser magma, and ranging in size from microscopic particles to truly enormous masses. Such xenoliths provide samples for inspection and analysis of the formations pierced by the pipes, and their study sheds a flood of light upon the nature of the earth's crust, from the immediate surface right down indeed to the universal ultrabasic shell or *sima*.

Ocular proof can thereby be obtained that beneath the covering of horizontal Permo-Triassic beds of the entire northern half of the Karroo region (which attains a thickness of a few miles towards the south-east), the basement rocks consist of granite, gneiss, hornblende-schist or granulites of various types, such indeed forming the continuation of the slightly sloping Archaean platform, that has been exposed by erosion further to the northwest. A practical turn is given by the fact that chalcopyrite is not uncommon in the blue ground at Kimberley, but mining has not gone deep enough to disclose the parent veins, which must intersect the underlying granite. Inclusions of quartzitic sandstone in the Saltpetre Kop breccias near Sutherland (Cape) suggest the intervention of the Table Mountain series between the Karroo beds and this crystalline basement. A small pipe on Roscoe near Postmasburg (Griqualand West) demonstrates the existence at a depth of over half a mile of the curious brecciated hematite ores of the Lower Griquatown series, and incidentally proves the remote date of their paragenesis. In the Mabuki Mine near Lake Victoria, Tanganyika Territory, the kimberlite carries xenoliths of red syenitic rocks, though such types are nowhere exposed among the phyllites penetrated by the vent. Of practical significance is the absence from the pipes throughout the northern Karroo or northwestern Orange Free State of lumps of coal or even of the peculiar grits and shales characterizing the "coal measure facies" of the Ecca series, which indicates that the productive phase thereof is not developed in the terrain underfoot.

Another common feature is the extraordinary way in which fragments derived from the higher levels have been carried down to great depths either by convective currents or by bodily sinking of the magma within the chimney. The preservation of fragments of now-vanished strata within the agglomerate of a volcanic neck is by no means a rare phenomenon, as, for example, in the great vent of central Arran, Scotland, with its relics of fossiliferous mesozoic beds, but southern Africa is particularly rich in fine instances thereof.

In the Kimberley Mine black Karroo shales are still found dis-

tributed through the "blue ground" at over 2500 feet below the base of the Karroo system, and masses of sandstone (some of it fossiliferous and indicative of the Beaufort series) occur in the adjacent mines, although neither the equivalent strata nor even the lower Ecca series rim the perforations, being indeed only represented many miles farther to the east.

Proof has now been obtained that Karroo strata must formerly have covered a large portion, if not the whole, of the Kaap Plateau to the west of Kimberley, a huge tract composed of ancient dolomites and other rocks, as is shown by inclusions of Karroo sediments and volcanics in half a dozen pipes distributed over the Postmasburg area. Corroboration thereof has been furnished by recent wells and borings which have disclosed concealed outliers of such beds. An economic aspect is given through the faint possibility that patches possessing the coal-bearing facies may somewhere be present, countersunk into the dolomite by sub-surface solution, just as has been the case in the Klip River valley to the southwest of Johannesburg.

While the Karroo (Stormberg) basalts cap the highest ground in and around Basutoland, and only the basal divisions of the system have been preserved over the lower-lying ground to the west, inclusions of such lavas have been discovered in quite a number of pipes located within an area extending from near Kroonstad in the northeast to near Victoria West in the southwest, and from Jagersfontein in the southeast to beyond Postmasburg in the northwest, a tract exceeding 30,000 square miles. Proof is hence forthcoming that these basalts extended in the past more than 250 miles further to the northwest than their present limits, all of which very extensive erosion must date from about the close of the Cretaceous epoch.

An interesting problem can next be considered, namely, the question of the completeness or otherwise of the Karroo sequence over this considerable stretch of country. The finding of inclusions of Lower and of either Middle or Upper Beaufort beds and also of the Stormberg "Cave Sandstone" in the Jagersfontein Mine, but the absence of any Molteno grits either here or in the

pipes further to the west, suggest that the Molteno group was not laid down in the area well to the northwest of Basutoland, and consequently that the succession in that direction held one or more disconformities, precisely as is known to be the case over the central and northern Transvaal.

A small pipe on Palmietfontein piercing the margin of the Pilandsberg alkaline igneous complex of the western Transvaal contains small inclusions derived therefrom, but of types unrepresented among the eruptive materials found *in situ;* presumably these were derived from horizons since removed by denudation. The Premier, the world's largest diamond mine, contains a gigantic inclusion of reddish quartzites and conglomerates, the size of which is gradually being revealed by mining operations, while boreholes have proved its limits in depth. It is a thick slab, oval in plan and nearly half a mile across its longer axis, and was punched out of the once overlying Waterberg series, becoming engulfed by the magma, with tilting and warping and a general subsidence to the extent of many hundreds of feet. Dipping westward at a moderately steep angle, it cuts the column of kimberlite into two portions which have had to be extracted separately, and this has proved a great hindrance in mining operations.

Significant is it that in South Africa such "descended inclusions" are all referable to formations having an age not younger than uppermost Karroo (Liassic), which hints that from that period down to the date of the kimberlite eruptions (probably late Cretaceous) deposition over the interior region failed; indeed other lines of evidence suggest active erosion during that interval.

Although from the nature of the case deductions having any economic bearing could only rarely be expected, it is worth while citing an instance in which the information thus gleaned proved of value. Near Kiamboi, on the Iramba Plateau of Tanganyika Territory, several kimberlite occurrences were recently discovered piercing granite, and one of these pipes contained inclusions of peculiar sandstones of unknown age. Certain sub-recent gravels and eluvial deposits situated just upstream thereof included no

such boulders and were moreover poor in heavy minerals, whereas those extending downstream of the pipe contained a fair proportion of similar sandstones, together with abundant detrital ilmenite and garnet; this heavy deposit was consequently referred to this rather than to any other of the pipes in the neighborhood. As tests of these gravels failed to produce any diamonds, it was concluded that the parent pipe would almost certainly prove equally barren. The latter was owned by a second syndicate, which made lengthy tests of the decomposed kimberlite of the pipe, but without recovering any diamonds therefrom; expectations were hence fully realized.

It might be remarked in conclusion that there are good reasons for suspecting a genetic connection between the kimberlites and the "rift volcanics" of Central and East Africa, though their age relationship is still in doubt.

ALEX. L. DUTOIT.

DISCUSSION AND COMMUNICATIONS

CRITERIA OF AGE RELATIONS OF MINERALS.

Sir: I read with great interest the stimulating article written by Bastin, Graton, Lindgren, Newhouse, Schwartz, and Short in the September–October, 1931, issue of this journal. Although written with primary regard to the age relationships of ore minerals, many of the criteria described are equally applicable to pegmatite minerals. On the other hand, many pegmatites contain a feature which is not included in the article under consideration, but which perhaps should be. I refer to open spaces formed through the solvent action of hydrothermal solutions.[1] Cavities of this type are certainly not unknown in ore deposits. I have seen caves in the Rico Wellington Mine, Rico, Colorado, lying between the ore body and unreplaced limestone. These were evidently caused by hydrothermal solutions that locally dissolved greater volumes of limestone than they were capable of replacing through the precipitation of ore minerals. Similar observations have been made by Hess: "Probably, in many [pegmatite] dikes solution takes place at some points faster than deposition, and vugs are formed. . . . The same process takes place during the formation of some ore veins. Many such solution cavities have been found in the Cripple Creek district, Colorado, a region of narrow veins." [2]

KENNETH K. LANDES.

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LAWRENCE, KANSAS.

[1] Landes, Kenneth K.: The Paragenesis of the Granite Pegmatites of Central Maine. Amer. Miner., vol. 10, pp. 364–6, 1925. Schaller, W. T.: The Genesis of Lithium Pegmatites. Am. Jour. Sci., vol. 10, p. 275, 1925. Palache, Charles; Davidson, S. C.; and Goranson, E. A.: The Hiddenite Deposit in Alexander County, North Carolina. Amer. Miner., vol. 15, p. 286, 1930.

[2] Hess, F. L.: The Natural History of the Pegmatites. Eng. & Min. Jour., vol. 120, p. 297, 1925.

REVIEWS

The Biography of Mother Earth. By HENRY SMITH WILLIAMS. Pp. 315, figs. 101, drawings (author's). R. M. McBride & Co., New York, 1931. Price, $5.00.

In this book the author traces his idea of the history of the earth from its beginnings. It is a biographical narrative written in a flowing, lucid style, unencumbered by technical phraseology, and is meant to intrigue the general reader rather than the scientist. We wish that more scientific books could be so interestingly written. It reads like a fairy tale, and it is one. The author shows how the continents, originally grouped around the South Pole, slowly floated northward as two huge cakes. The first cake to break off consisted of what is now North America, Europe and Asia. In its northward journey through the ocean wastes at a rate of only a few feet a century, it sailed from rigorous Antarctic ice fields to sunny equatorial regions where earlier glaciation disappeared and luxuriant vegetation flourished to form coal fields that are now in Spitzbergen. And the journey continued until this huge land mass, as a single unit, enveloped the north polar region. Here refrigeration again took place, and the ice sheet of the Glacial Period overspread the land.

Africa and India, likewise floating northward, collided with Asia to form the great earth wrinkles that gave rise to the Alpine-Himalayan chain of mountains. The propelling force is supplied according to the "geoid-balance" hypothesis, a pet theory which the author is promoting.

The reader is floated through the geologic ages, which, according to the author, have a span of 2,850,000,000 years, and is given glimpses of the starting of unicellular life, its development through the ages of fishes, dinosaurs, birds and mammals. The reader is told exactly how and why these forms started and became extinct. Scores of artistic sketches help make clear a picture that is but lightly skimmed by the pen. The reader is rushed breathlessly across floating continents with fighting dinosaurs, frozen mastodons, grinding ice sheets, and cave men.

If the book were written as a fairy tale it would be charming. But who would wish to make a fairy tale out of the biography of Mother Earth? Obviously the author did not intend it so any more than did Huxley in his beautifully written story of a piece of chalk. Unfortunately, however, the author has intermixed much truth with fiction. It is evident that he has read widely of books on geology and has tran-

scribed the findings of master geologists in fascinating language that they themselves could not achieve. But it is equally evident that the author's reading has not been discriminating, that he has failed to distinguish fact from hypothesis, and that he is not at home in this field of knowledge and thought. He presents what might be called flights of imagination as working hypotheses, and sets up delightful imaginative theories that not only are unsupported by geologic evidence but are contrary to the best scientific data available. It is easy to state, without supporting evidence, that the known geologic periods have a span of 2,850 million years, and that the Paleozoic era alone has 875 million years, the Mesozoic 450 million, the Tertiary 300 million, and the Quaternary 50 million, a total of 1675 million years; and to date the Quaternary, "(*Anno Vitae* 3,150,000,000–3,200,000,000)." But this is simply a fairy tale which conflicts with cold facts of scientific data that apparently are unfamiliar to the author. This subject has long been studied by geologists, and the rather precise determination of the age of rocks, based on the known rate of disintegration of radioactive substances such as uranium into radium and lead, shows that the oldest rocks tested have an age of 1850 million years and that all the geologic eras back to the beginning of the Paleozoic fall within a span of 500 million years.

Also, the flights of the continents from the South to the North Pole must be taken as flights of imagination. There are no data to substantiate them. Hypotheses, however faulty, must rest on some factual data, and such are lacking. The author has evidently swallowed, hook, line, and sinker, the Wegener hypothesis of continental drift. However, the Wegener theory is purely a hypothesis, believed by a few and disputed by many. Regardless of whether it has the flavor of truth or untruth, it is far from being an established fact. Even Wegener would turn in his icy Greenland grave were he to hear the author's unwarranted extension of his original idea.

Even more fantastic is the author's description (based on Wegener's hypothesis) of the northern continents during the Glacial Period. Greenland lay athwart the North Pole, Labrador and Scandinavia touching it at opposite sides, both of these countries being then within the 80th parallel of latitude. North America pivoted westward with the pivotal point in northwest Canada; Europe pivoted eastward to fuse with Asia. Labrador, according to the author, swung down from the 80th parallel of latitude to the 55th parallel; northern Florida from Lat. 50, Long. 60 W., to Lat. 35, Long. 75 W. What a swing, and all since within the Glacial Period! A delightfully simple explanation of the Glacial Period, if true!

How is the poor general reader, unversed in the intricacies of modern geology, to differentiate hypotheses reared in imagination from those based on factual data. The author of this book has not helped him, unless

the treatise be considered simply as a fairy tale. It were better if the book had not been written. It gives an erroneous picture of the history of the earth. As Professor Dodge has stated, "facts without hypotheses are dead and hypotheses without facts might as well be."

ALAN BATEMAN.

Report on Tour of Inspection of the Oil Fields of the United States and Argentina and on Oil Prospects in Australia. By W. G. WOOLNOUGH. Pp. 118, figs. 36. Canberra, Australia, 1931. Price 5 s.

Professor Woolnough, as geological adviser to the Commonwealth government of Australia, made a rather thorough trip of inspection of American oil fields and American production companies. His interest was focused rather on the geological methods and on prospecting than on production technology. The reviewer can find a few of Professor Woolnough's impressions with which he would differ, as, for example, that "In no instance has the result of geophysical work been directly followed by production drilling," or that "All the major companies have fleets of planes for the use of their land and geological departments." His praise of American oil geologists and oil geological methods is pleasant but the writer feels that the American oil geologist is not the super-geologist and the American oil company's geologic work is not as perfect as depicted by him. But Professor Woolnough has caught the spirit of the American producing oil business and this report is a most readable and interesting, brief and simply stated, but thorough account of the American oil geology and exploration.

DONALD C. BARTON.

Coral Reefs and Atolls. By J. S. GARDINER. Pp. 181, pls. 15, figs. 33. Macmillan & Co., London, 1931. Price, $4.25.

This book represents a course of lectures delivered at the Lowell Institute at Boston, in February, 1930, and the conclusions are the results of thirty-five years' work on the problem. Most of the biological observations were made by the author during five years of work on the reefs. The lecture headings give an idea of the contents: I, Fringing, Barrier, and Atoll Reefs; II, Island Formations; III, Natural History of Corals; IV, Other Plant and Animal Reef Builders; V, Other Organisms of Reefs; VI, Distribution of Reefs; VII, Atolls and Their Lagoons; VIII, Foundations of Atolls.

Many new data, particularly biologic, are presented. The author concludes that our knowledge of the platforms is insufficient and that, given a stationary bank at less than 50 fathoms below the surface of a tropical sea, an atoll will result in due time.

The book is well printed and illustrated and is of interest to all students of geology and biology.

BOOKS RECEIVED.

By

DAVID GALLAGHER.

Shorter Contributions to General Geology, 1930. Pp. 180, pls. 43, figs. 11. U. S. Geol. Surv. Prof. Paper 165. Washington, 1931. Price, $1.25. Contains: (*A*) Lithologic studies of fine-grained Upper Cretaceous sedimentary rocks of the Black Hills region, by W. W. RUBEY, (*B*) A flora of Green River age in the Wind River Basin of Wyoming, by E. W. BERRY, (*C*) Geology of the eastern part of the Santa Monica Mountains, Los Angeles County, Calif., by H. W. HOOTS, (*D*) Geology of the Big Snowy Mountains, Mont., by FRANK REEVES, (*E*) The kaolin minerals, by C. S. ROSS AND P. F. KERR.

The Kaiparowits Region. A Geographic and Geologic Reconnaissance of Parts of Utah and Arizona. By H. E. GREGORY AND R. C. MOORE. Pp. 161, pls. 31, figs. 9. U. S. Geol. Surv. Prof. Paper 164. Washington, 1931. Price, $1.05. Geography, stratigraphy, physiography, structural and economic geology of the interesting region S.W. and W. of Gilbert's Henry Mts.

Glaciation in Alaska. By S. R. CAPPS. Pp. 8, pls. 2, figs. 2. U. S. Geol. Surv. Prof. Paper 170-A. Washington, 1931. Price, 15 cts.

Fifty-second Annual Report of the Director of the U. S. Geological Survey for Year Ending June 30, 1931. Pp. 95. U. S. Dept. of the Interior. Washington, 1931. Price, 15 cts.

The Slana District, Upper Copper River Region, Alaska. By F. H. MOFFIT. Pp. 14, pls. 1. U. S. Geol. Surv. Bull. 824-B. Washington, 1931. Price, 5 cts.

The Lake Clark-Mulchatna Region, Alaska. By S. R. CAPPS. Pp. 30, 1 pl., 1 fig. U. S. Geol. Surv. Bull. 824-C. Washington, 1931. Price, 10 cts.

Occurrence of Gypsum at Iyoukeen Cove, Chichagof Island, Alaska. By B. D. STEWART. Pp. 9. U. S. Geol. Surv. Bull. 824-E. Washington, 1931. Price, 5 cts.

Mineral Industry of Alaska in 1930, and Administrative Report. By P. S. SMITH. Pp. 129, figs. 3. U. S. Geol. Surv. Bull. 836-A. Washington, 1931. Price, 20 cts. Production statistics, bibliography.

Notes on the Geography and Geology of Lituya Bay, Alaska. By J. B. MERTIE, JR. Pp. 19, map. U. S. Geol. Surv. Bull. 836-B. Washington, 1931. Price, 5 cts.

Geology and Mineral Resources of the Quakertown-Doylestown, District, Penn. and N. J. By F. BASCOM, E. T. WHERRY, G. W. STOSE, AND A. I. JONAS. Pp. 62, pls. 4, figs. 3. U. S. Geol. Surv. Bull. 828.

Washington, 1931. Price, 40 cts. Stratigraphy, structure, historical and economic geology of the region.

Gaffney-Kings Mountain Folio, So. Carolina-No. Carolina. By A. KEITH. Pp. 13, maps 8, illus. 11. U. S. Geol. Surv., Geologic Atlas of the U. S., Folio No. 222. Washington, 1931. Price, 50 cts.

Surface Water Supply of the United States, Water Supply Papers, U. S. Geol. Surv. Gaging-station records. 1928, Part III, W. S. P. 663. **1929, Part I,** W. S. P. 681; **Part IV,** W. S. P. 684; **Part VII,** W. S. P. 687; **Part IX,** W. S. P. 689; **Part XII,** W. S. P. 693. **1930, Part X,** W. S. P. 705.

Gold Fields of Nova Scotia. By W. MALCOLM AND E. R. FARIBAULT. Pp. 253, pls. 40, figs. 10, plans and sections 3, 1 map. Can. Geol. Surv. Mem. 156. Ottawa, 1929. Price, 50 cts. General geology, economic geology of the primary gold deposits, placer deposits, and descriptions of the gold districts.

Studies of the Geophysical Methods, 1928 and 1929. By J. B. MAWDSLEY, et al. Pp. 225, pl. 1, figs. 66, plans 11. Can. Geol. Surv. Mem. 165. Ottawa, 1931. Price, 45 cts. "This report, based on field work carried out in conjunction with prospecting companies using electrical methods, is an attempt to meet the general demand for unbiased information concerning prospecting by electrical methods."

Late-Glacial Correlations and Ice Recession in Manitoba. By E. ANTEVS. Pp. 76, figs. 7, 1 pl. Canada Geol. Surv. Mem. 168. Ottawa, 1931. Price, 15 cts. Quaternary history of North America with emphasis on glaciation and glacial lakes.

Canada Geol. Survey, Summary Report, 1930, Part A. Pp. 196, figs. 10, pls. 3, maps 2. Ottawa, 1931. Contains eleven papers on British Columbia: Mining Industry 1930, by W. E. COCKFIELD; Explorations and Mineral Properties in Taku District, by F. A. KERR; Buttle Lake Map-area, by H. C. GUNNING; Lightning Peak, St. Paul Claims, Aberdeen Mt. Deposits, Osoyoos District, by C. E. CAIRNES; Kamloops District, by J. F. WALKER; Corbin Coal Field, by B. R. MACKAY; Deep Borings, by W. A. JOHNSON.

Canada Geol. Survey, Summary Report, 1930, Part B. Pp. 103, figs. 7. Ottawa, 1931. Contains: Milk River Area and Red Coulee Oil Field, Alberta, by C. S. EVANS; Willowbunch Area Clay, by F. H. MCLEARN; Ground Water, Moose Jaw, Saskatchewan, by W. A. JOHNSTON AND R. T. D. WICKENDEN; Interglacial Deposits, Southern Saskatchewan, by R. T. D. WICKENDEN; Southern Manitoba Cretaceous, by R. T. D. WICKENDEN; Deep Borings, Prairie Provinces, by W. A. JOHNSTON.

Canada Geol. Survey, Summary Report, 1930, Part C. Pp. 131, figs. 8. Ottawa, 1931. Geology and Mineral Deposits of a Part of Northwest Manitoba, by J. F. WRIGHT.

SCIENTIFIC NOTES AND NEWS

A. L. Hall, Director of the Geological Survey, Union of So. Africa, has retired after twenty-nine years of work with the Survey.

W. S. McCann has been appointed joint manager of the Consolidated Goldfields of South Africa.

Arthur Notman has been elected president of the Mining and Metallurgical Society of America.

T. L. Tanton, of the Canada Geological Survey, recently lectured at Queen's University on the iron deposits of Lake Superior, the silver deposits of Lake Superior, and liquid immiscibility in lavas.

E. J. Dunn, who has been government geologist of Victoria, Australia, is now consulting geologist for Clunes Goldfield.

Sydney H. Ball, of New York City, gave an address before the Royal Canadian Institute on January 23 at Toronto, on The Diamond and the Diamond Industry.

Austin F. Rogers, of Stanford University, has named a new barium silicate mineral which he recently identified sanbornite, in honor of Frank Sanborn, of the California Bureau of Mines.

A. E. Fath has returned to this country after two years in Germany investigating oil possibilities there.

Chester W. Washburne left New York last month for a lengthy professional trip.

Sydney E. Helprin has been appointed assistant curator of geology in the New York Museum of Natural History.

Northwestern University in an exchange with the University of Cincinnati heard W. H. Bucher on "Life in the Cincinnati Seas," "The Interpretation of Joints," "Cryptovolcanic Structures," and "Aspects of Megatectonics." C. H. Behre, Jr., of Northwestern University, gave three exchange lectures at Cincinnati dealing with phases of ore deposition, one on the Geology of Leadville and one on Slate Deposits. He also spoke before the Geological Society of Cincinnati on Physiographic Research in Central Colorado.

The users of Fuess instruments will be glad to learn that R. Fuess is establishing an agency in New York.

The American Association of Petroleum Geologists will hold its seventeenth annual meeting at Oklahoma City March 24–26, with headquarters at the Biltmore Hotel. The technical program is in charge of F. H. Lahee, Box 2880, Dallas, Texas. Two field trips have been arranged, one

to Oklahoma City field on March 25 and one to Arbuckle Mountains on March 26.

The Emmons Memorial Fellowship in Economic Geology is available for this year (stipend about $1200). Applicants should be qualified by training and experience to investigate some problem in economic geology and should submit a definite statement of their problem to the Committee under whose oversight the work will be undertaken at any institution approved by them. The Fellow must give his entire time to the problem, which may be used as a doctorate dissertation. Applications and accompanying testimonials should be submitted not later than April 15. Application blanks and further information may be obtained from Alan M. Bateman, Charles P. Berkey, Waldemar Lindgren, or the Secretary, Columbia University.

The American Institute of Mining and Metallurgy held its 141st meeting on February 15–18 in New York. At the mining geology session the following papers were presented: Notes on Steel-Making Alloys, by P. M. Tyler; Nickel Resources, Production and Utilization, by E. S. Moore; Molybdenite Deposits, Climax, Colo., and others, by J. W. Vanderwilt; Prospecting for Gold in the Shield Areas of the World, by W. H. Emmons; Recent Discovery of Cinnabar in Arkansas, by G. C. Branner; Geology and Economics of Tin Mining, Cornwall, by E. R. Lilley; Ceramic Tests in Subsurface Correlation, by C. E. Dobbin and E. A. Swedenborg; Mining Geology and Mine Exploration, by R. D. Hoffman. There were also many excellent papers on Petroleum and Geophysical Prospecting.

At Northwestern University in the Department of Geology and Geography during the first semester of the current academic year visiting lecturers and their subjects included: Dr. G. H. Cady, Ill. Geol. Survey, Classification of Coal; Prof. A. N. Winchell, Univ. of Wisconsin, The Origin of the Graphite in Veins and Pegmatites; Dr. G. F. Loughlin, U. S. Geol. Survey, The Ore Deposits of Cripple Creek, Colorado; Dr. D. G. Thompson, U. S. Geol. Survey, The Work of the Ground Water Section of the U. S. Geological Survey; Prof. A. C. Noé, University of Chicago, A Geologist in Russia; Mr. Thos. A. Hendricks, U. S. Geol. Survey, Oklahoma Coal Measures; Dr. T. S. Lovering, U. S. Geol. Survey, The Geology of the Moffat Tunnel, and The Mineral Belt of the Front Range, Colorado.

The recently published 20-volume index (336 pages) of ECONOMIC GEOLOGY for 1905 to 1925, compiled by J. M. Nickles, may be obtained for $3.00 from W. S. Bayley, University of Illinois, Urbana, Ill.